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FLUVIAL GEOMORPHOLOGY AND RIVER-GRAVEL MINING:

A Guide for Planners, Case Studies Included



CALIFORNIA
DEPARTMENT
OF CONSERVATION

Division of Mines and Geology

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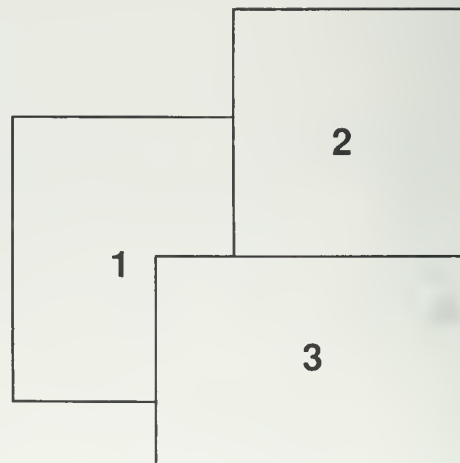
Front Cover:

Sand and gravel, with widespread importance as construction aggregate, is often mined in the alluvial reaches of rivers and streams. The physical and environmental setting varies greatly between locations that could potentially supply this resource. Three actively mined channel reaches are pictured on the cover. These are:

Photo 1. The middle reach of the Russian River near Santa Rosa, California.

Photo 2. The Mad River near Eureka, California.

Photo 3. The lower channel reach of Cache Creek near Sacramento, California.



FLUVIAL GEOMORPHOLOGY AND RIVER-GRAVEL MINING: A Guide for Planners, Case Studies Included

By

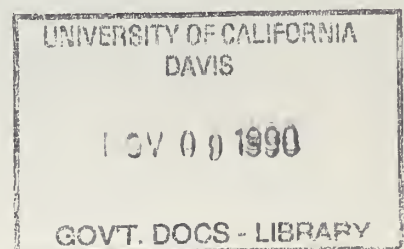
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1990

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SUMMARY

Gravel is extracted from many rivers for use in industry or as part of flood-control programs. In few cases is extraction carried out according to a plan which includes an assessment of possible effects on rivers. This report is intended to guide planners who may be undertaking a program to assess, predict, or manage effects of gravel extraction. The publication is organized into four parts, as summarized below.

Effects on Rivers of Gravel Extraction (p.1-2).

The effects of gravel extraction on river morphology and sediment transport are summarized from published field studies and from analysis of several additional rivers on which we have supplemented unpublished studies.

The summarized effects include:

- (1) Extraction of bed material in excess of replenishment by transport from upstream causes the bed to lower (degrade) upstream and downstream of the site of removal.
- (2) Bed degradation can undermine bridge supports, pipe lines, or other structures.
- (3) Degradation may change the morphology of the riverbed, which constitutes one aspect of the aquatic habitat.
- (4) Degradation can deplete the entire depth of gravelly bed material, exposing other substrates that may underlie the gravel, which could in turn affect the quality of aquatic habitat.
- (5) If a floodplain aquifer drains to the stream, groundwater levels can be lowered as a result of bed degradation.
- (6) Lowering of the water table can destroy riparian vegetation.
- (7) Flooding is reduced as bed elevations and flood heights decrease, reducing hazard for human occupancy of floodplains and the chance of damage to engineering works.
- (8) The supply of overbank sediments to floodplains is reduced as flood heights decrease.
- (9) Rapid bed degradation may induce bank collapse and erosion by increasing the heights of banks.
- (10) In rivers in which sediments are accumulating on the bed (aggrading) in the undisturbed condition, gravel extraction can slow or stop aggradation, thereby maintaining the channel's capacity to convey flood waters.
- (11) The reduction in size or height of bars can cause adjacent banks to erode more rapidly or to stabilize, depending on how much gravel is removed, the distribution of removal, and on the geometry of the particular bend.

- (12) Removal of gravel from bars may cause downstream bars to erode if they subsequently receive less bed material than is carried downstream from them by fluvial transport.

Assessing Gravel Harvesting Effects (p. 2-6)

In order to characterize the supply of gravel to downstream reaches and to assess or predict the effects of gravel removal, it is necessary to understand how sediment is produced and transported and how it interacts with river-channel morphology. This part summarizes the following influences on river channel geomorphology.

Processes of basin sediment production are reviewed (p.2-3) because the location and manner in which sediment is contributed to rivers influences the amount and durability of gravel supplied to downstream reaches. A combination of observation and measurement in the field and on aerial photographs may be used to identify, locate, and quantify sediment sources, and to define how they change through time and as a result of changes in land use.

Processes by which sediment is transported along rivers and the controls on those processes are summarized (p.3-4). Most material within the bed of gravelly rivers is transported as bedload, which accounts for a relatively small proportion of the total load of most rivers. Most material is typically transported during high flows which occur on only several days per year.

The location and behavior of the depositional reaches of rivers typically exploited for gravel are explained in light of the downstream reduction in channel gradient and transporting ability, and resulting gravel bar deposition (p. 4-5). A combination of field sampling, field observations, and analysis of archival materials, such as aerial photographs, maps, and survey data, can be used to characterize the patterns of sediment transport and deposition and of changes in channel morphology. The same approach may be used to determine the effects of various land and channel uses on downstream patterns of sediment transport and channel morphology.

Processes of bedload transport, gravel-bar accretion, floodplain formation, and channel migration at river bends are summarized (p. 5). Methods for estimating bedload transport are reviewed. The report stresses that each approach must be applied only under the conditions for which it is valid, that it is desirable whenever possible to use several different methods, and that it should almost always be possible to derive a usable estimate of transport in a given river (p.6-7). Equations for bedload transport can be useful if carefully employed, but the results should always be checked against some independent field evidence.

Management of Gravel Mining Effects (p. 7-8)

A general approach is proposed for the management of gravel extraction from rivers:

- (1) Appropriate rates and locations of gravel extraction-should be determined based on:
 - (a) The rate of upstream replenishment.
 - (b) Whether the riverbed elevation under undisturbed conditions remains the same over periods of decades, or if not, a determination of the aggradation or degradation rate.
 - (c) Historical patterns of sediment transport, bar growth, and bank erosion in particular bends.
 - (d) Projection of anticipated effects on the riverbed and banks, including, when possible, analysis of present or past effects of gravel extraction at various rates.
 - (e) Analysis of the desirability or acceptability of the anticipated effects of extraction at different rates.
- (2) Records of extraction quantities should be maintained.
- (3) Monitoring subsequent to implementation of a regulated harvesting rate should document effects to the riverbed, banks, and bars, using cross-sections and aerial photographs. The data should be analyzed immediately after collection.
- (4) Permitted extraction rates should be periodically reviewed in light of the information generated by the monitoring program.

Case Studies (p. 8-27)

Case histories taken from the western United States and New Zealand are presented to illustrate how effects of gravel extraction on river channels have been assessed and managed. The case studies include the following groupings of rivers:

- (1) Perennial rivers in which bed degradation and related effects have resulted from gravel extraction (Russian River and Cache Creek in California; Humptulips, Wynoochee, and Satsop rivers in Washington; Lower Manawatu River in New Zealand).
- (2) An intermittent, arid-land stream in which in-channel extraction caused catastrophic channel erosion (Tujunga Wash, California).
- (3) Aggrading rivers in which gravel extraction has been used to reduce the rate of aggradation or to stabilize the bed at a constant elevation (White River, Washington; Redwood Creek, California).
- (4) A channel in which bar operations modified adjacent bars and banks (Skykomish River, Washington).

NOTE ON UNITS

It is characteristic of the literature on rivers that both English and metric units have been used. Planners must therefore work with both sets of units, and so both have been used in this text. Conversions for units used are as follows:

$$1 \text{ mile} = 1.61 \text{ km}$$

$$1 \text{ yd}^3 = 0.765 \text{ m}^3$$

$$1 \text{ cfs} = 0.0283 \text{ m}^3/\text{sec}$$

$$1 \text{ km} = 0.621 \text{ mile}$$

$$1 \text{ m}^3 = 1.31 \text{ yd}^3$$

$$1 \text{ m}^3/\text{sec} = 35.3 \text{ cfs}$$

FLUVIAL GEOMORPHOLOGY AND RIVER-GRAVEL MINING:

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by Brian Collins and Thomas Dunne, Geologists

INTRODUCTION

Statement of the Problem

Gravel is extracted from bars and the low-water channel of many rivers. In most cases, material is extracted to obtain a supply of aggregate for industrial use. Gravel is also removed from some channels to restore or maintain flood capacity. Gravel extraction has been documented to affect patterns of bank erosion, and to change the elevation and morphology of the riverbed. These changes can in turn affect fish and wildlife habitat, flooding, and engineering structures.

Purpose of this Publication

This publication summarizes how an understanding of river-channel geomorphology may be used to assess, predict, and manage the effects of gravel extraction in a particular river. It is intended to guide the planner who must determine what, if any, studies may be needed to assess his or her situation, and to provide guidance in the

design of those investigations. The knowledge gained from reading of this publication will not eliminate the need for technical assistance from a geomorphologist or hydrologist. Examples and case studies included in the report are drawn chiefly from the western United States, but the principles illustrated apply to gravel-bed rivers of other regions.

Outline of the Publication

The report is in four parts. The documented effects of gravel extraction on river morphology are first summarized. Aspects of river geomorphology useful for assessing gravel extraction effects on rivers are then reviewed. Third, a general approach to managing gravel extraction is proposed. Finally, a series of case studies illustrates how gravel mining effects have been assessed and managed in several river basins. The first three parts of the report can be read as a summary without the detailed case studies.

EFFECTS OF GRAVEL EXTRACTION ON RIVER MORPHOLOGY AND SEDIMENT TRANSPORT

The interaction between in-channel gravel extraction and channel morphology has been studied on few rivers. The following summary of gravel extraction effects is based in part on a review of published studies, which include: the Humptulips, Wynoochee, and Satsop rivers, Washington (Collins and Dunne, 1989); the Manawatu River, New Zealand (Page and Heerdegen, 1985); Tujunga Wash, California (Scott, 1973; Bull and Scott, 1974); Naugatuck River, Connecticut (MacDonald, 1988); and the Mississippi River (Lagasse and others, 1980). The summary is also based on an analysis of additional rivers for which unpublished reports, conference proceedings papers, or other data are available. For the preparation of this publication, a review and synthesis of these studies or data were supplemented by field visits and a limited amount of additional data analysis. This latter category includes the Skykomish and White rivers in Washington, and the Russian River, Cache Creek, and Redwood Creek in California. Each of these rivers is discussed in a case study later in the text; the unpublished reports and other sources of data for each are listed within the text.

This publication is restricted to a discussion of extraction from bars or the low-water bed of gravelly river channels. It does not consider floodplain gravel extraction. Although the effects on river morphology and sediment transport associated with the capture of floodplain pits by meandering streams have not received a systematic treatment in the literature, various case studies are available. Examples include: the Naugatuck River, Connecticut (MacDonald, 1988); the Yakima River, Washington (Dunne and Leopold, 1978); and several Arctic streams (Woodward-Clyde Consultants, 1980).

In assessing the past or probable future impact of gravel extraction, the river and its environs should be examined for specific evidence of, or potential for, each of the following effects.

- (1) Extraction of bed material in excess of the replenishment from upstream causes bed degradation. Degradation can extend upstream and downstream of an individual extraction operation, and can result from mining of the bed either in or above the low-water channel.
- (2) As a result of bed degradation, bridge supports can be undermined, and pipelines or other structures buried within river beds can be exposed.

- (3) Bed degradation may change the morphology of the river channel, which could affect aquatic habitat and salmonid spawning sites.
- (4) Degradation can deplete the entire depth of gravel on a channel bed, exposing other substrates that may underlie the gravel, which in turn may affect aquatic habitat. The potential for gravel bed depletion depends on the thickness of gravel deposits above another substrate.
- (5) If a floodplain aquifer discharges to the stream, groundwater levels can be lowered as a result of channel degradation. Lowering of the water table would reduce aquifer storage capacity, increase depth to groundwater, and drain wetlands, but enhance some uses of seasonally saturated soils where groundwater levels are at or near the ground surface.
- (6) Lowering of the groundwater can destroy riparian vegetation in the short term. Eventually vegetation can colonize lower elevation banks as they are exposed. Destruction of riparian vegetation can in turn adversely affect fish and wildlife habitat. In streams where vegetation acts to stabilize the banks, bank erosion may be increased as a result of vegetation destruction.
- (7) The frequency and magnitude of overbank flooding are lessened as bed elevations and flood heights decrease, reducing hazard for human occupancy of floodplains and the chances of flood damage to bridge spans. Therefore, gravel extraction to increase flood conveyance capacities of channels may be part of a program of flood control.
- (8) Rivers migrate across the floodplain by eroding the outside bank of a bend and depositing material on a point bar on the inside bank. With time the gravel bar on the inside of the bend is covered with fine sediments and organic materials from overbank flooding, eventually making the soil suitable for vegetation. However, if the accretion occurs while the riverbed is rapidly lowering, the accreted land will be stranded above the active floodplain as a terrace. Newly arrested or existing floodplains may no longer be supplied during floods with water and fine, organic-rich sediments, which are important for some agricultural land uses.
- (9) Rapid bed degradation may induce lateral bank erosion by increasing the height of banks, which are then more prone to undercutting and failure.
- (10) The reduction in size or height of gravel bars can cause either the erosion or the stabilization of upstream and downstream banks. The existence of the point bar tends to force the current toward the opposite bank, undermining it. Removal of the point bar may therefore stabilize the opposite bank. However, lowering of the point bar may also have a destabilizing effect on banks as a greater portion of the flow follows a more direct path downstream, increasing the erosivity of the river on the outside bank of the next bend downstream. Prediction for particular river bends requires careful field study of the geometry and hydraulics of the specific bends.
- (11) Removal of gravel from bars may cause erosion of downstream bars by interrupting the supply of gravel to them while the river maintains its capacity for transporting gravel from them.
- (12) Some dredging operations result in the preferential removal of gravel from mixed sand and gravel beds. Lagasse and others (1980) suggest that a reduction in the gravel supply in such a river can affect channel stability, because bars, which are armored by gravel, could be destabilized as a result of the decrease in gravel supply. Lagasse and others (1980) speculate that an increase in the number of divided flow reaches in the lower Mississippi River may have stemmed in part from an observed decrease in bed material size. This possible effect is relevant to few perennial rivers of the Pacific states, because extraction operations usually do not preferentially remove coarser particles from the bed.

ASSESSING GRAVEL MINING EFFECTS

To describe or predict how current or planned gravel extraction operations may affect channel beds or banks, an understanding must be developed of:

- (1) What factors influence the supply of sediment to rivers.
- (2) How rivers transport and deposit sediment.
- (3) How sediment transport and deposition interact with the morphology of the channel.

Sediment Sources

Sediment is contributed to rivers from a variety of sources within a drainage basin. These include:

- (1) The assortment of mass wasting processes, including landsliding and soil creep, by which gravity moves soil and rock downslope.
- (2) Erosion of hillslopes by water.
- (3) Erosion by rivers of their beds and banks.

These various sources produce sediment with varied grain sizes and durabilities, and thus affect differently the quantity and quality of gravel transported downstream. The location of sediment sources is also important because coarse material contributed to a river far upstream from zones of gravel deposition will be broken down into sands and silts during transport; sediment sources farther downstream supply more of their coarse particles to the depositional zone.

The dominant sediment sources in a drainage basin, their location, and their relative importance may be determined by a combination of aerial photographic analysis and field observations.

The following are typical sediment sources and their characteristics relevant to gravel supply:

Water Erosion: Water erosion occurs when the intensity of rainfall exceeds the infiltration capacity of the soil, and overland flow is generated. In arid and semiarid regions, runoff and erosion are generated during storms over widespread portions of the landscape, producing largely silt- and sand-sized sediment. In humid and sub-humid regions with a dense vegetation cover, generation of overland flow and erosion are typically restricted to disturbed areas such as forest roads and construction sites. Surface erosion produces almost exclusively sediments which are sand-sized and smaller (Reid and Dunne, 1984).

Landslides: Landslides typically are triggered by the buildup of soil-water pressures during prolonged, heavy rainstorms. Shallow landslides usually evacuate the entire mantle of colluvium (soil and weathered rock in transport down hillslopes by mass-wasting processes). Deep-seated failures also include the underlying weathered rock. Sediment produced by landsliding reflects the grain-size distribution of the hillslope materials and may often reflect a wide range of particle sizes from clay to boulders.

The location and importance of landslides can be determined from aerial photographs in combination with field checking. The frequency of landsliding is determined by mapping the occurrence of landslides on a sequence of aerial photographs. Volumes may be obtained by measuring the dimensions of representative landslide scars and constructing a relation between the measured volume and planimetric areas of the scars. The relation may then be used to estimate the volumes of all mapped landslides.

The rate of landsliding can vary greatly in response to differences in land use and to large storms; this variation in turn affects the supply of gravel to rivers. Logging and the accompanying road building commonly increase the rate of landsliding, frequently by increasing the occurrence of landslides associated with roads (Reid and others, 1981; Sidle and others, 1985). Madej (1982) and Lyons and Beschta (1983) have documented that increased sediment influx from logging-related landslides has caused river channels to widen and aggrade (Madej, 1982; Lyons and Beschta, 1983). Other factors which can bring about a short-term increase in the supply of coarse sediment to rivers from landsliding include: (1) large storms (Kelsey, 1980), particularly when combined with logging and road building (Nolan and others, in press; Lyons and Beschta, 1983), and (2) landslides triggered by large earthquakes (Pearce and Watson, 1986). Because changes in landslide rates may be recognized and measured through time by examining sequences of aerial photos, it is possible to identify the importance of land-use changes, rare storm events, large earthquakes, or other factors which can influence the long-term supply of coarse sediment.

Soil Creep: Soil creep is the slow downslope movement of soil due to disturbances such as frost heaving, tree-throw, and animal activity. It is most rapid on steeper slopes. Creep typically supplies sediment to streambanks, where it enters the river by bank erosion, or to bedrock swales, which slowly fill with soil and periodically discharge the sediment by landsliding at intervals of hundreds to thousands of years.

Bank Erosion: Erosion of streambanks is a source of sediment when banks are being supplied with sediment from upslope by creep or other mass wasting processes. Bank erosion also produces sediment when the eroded banks are terraces, higher than the present floodplain. A stream flowing across a floodplain, without undergoing any systematic widening, does not produce a net sediment influx to the channel when it erodes its banks, because the volume of sediment eroded from the outside of a bend is roughly equal to the volume deposited on the inner bank. Erosion of terraces can be identified on aerial photographs and in the field as a significant source of sediment, and can be quantified by measuring the change in terrace area between sequential photographs and multiplying it by the average difference in height between the terrace and the floodplain bank height. Terrace and floodplain elevation differences can be measured in the field from maps or from the aerial photographs.

Riverbed Erosion: Rivers that are cutting downward produce sediment by the development of canyons or valleys. The grain-size distribution of sediment contributed to the river is determined by the range in grain sizes composing the geologic material through which the river is incising and the transporting ability of the river.

Long-term rates of river trenching from the present topography can sometimes be quantified if inferences can be made about the topography at an earlier time. For example, if recent diking or channelization has focused the flow of several channels into one, the channel may have deeply incised its floodplain. The volume removed can be estimated from the surveying of a few, representative cross-sectional areas and of the length of incision. The rate of downcutting in rapidly incising rivers may be measurable from records of river elevations at river gages and at bridge sites.

Sediment Transport

Of the variables affecting the ability of a river to transport sediment, depth and surface slope of the water are the most important. Transporting ability increases as depth and thus discharge increase and as river gradient increases. The transporting ability typically increases more rapidly than does the increase in flow rate and depth. Because of this rapid rise in transport rate with increasing discharge, the majority of the annual transport may occur during one or several storms or during a few days of rapid snowmelt runoff.

Sediment which is contributed to a river channel may be transported as bedload or suspended load. Bedload is that portion of the total sediment load of a river which is transported by sliding, rolling, and bouncing over the bed, and includes the coarsest portion of the river load. During measurement, bedload is defined as that portion of the load which enters a 3-inch high square orifice resting on the bed (Emmett, 1981). Suspended load is the portion of the load which is supported by turbulent eddies within the column of flowing water. Suspended load includes the finer portion of the bed material which is only intermittently suspended within the flow as well as wash load, comprising particles too fine to settle to the channel bed. Suspended load as measured is that portion of the load which enters a standardized sampler which cannot approach closer than 3 inches from the bed.

The nature of bedload transport differs between a river with a sandy bed and one with a gravelly bed. In a sand-bed river, the particles on the bed are more readily entrained as flow rate increases; and although the transport rate may be slight, transport can be initiated at a relatively low flow rate. In a river with a gravel bed, there is transport only above a relatively high flow which in many rivers may occur less than several times a year.

The nature of suspended sediment transport also varies between sand- and gravel-bed rivers. In a sand-bed river, the bed material includes a large proportion of suspendible sediment. Suspendible fine sediment is also contributed directly to the channel during storms from hillslope erosion or mass wasting. In a gravelly river, grain-size distribution of bed material is approximately equivalent to that of the bedload. Storage of suspendible sediment in a gravel bed is mainly confined to the spaces between larger particles in the upper several inches of the bed (Milhous, 1982). In a gravel-bed river, suspended sediment transport is more dependent on the supply of sediment from sources outside the channel, because the bed material is a less significant source of sediment.

During transport, individual particles of sediment are abraded and diminished in size. In addition, sediment is temporarily deposited in bars on the inside of bends. This sediment later becomes incorporated into the floodplain as the river migrates and the bar accretes outward. Eventually this gravel will be eroded by the channel as the river migrates back in the future. However, during storage, lasting tens to thousands of years, the gravel particles are subject to mechanical and chemical weathering. Weathering during storage makes the gravels more susceptible to abrasion when they subsequently re-enter and are transported within the active channel. The finer, weathered, and abraded particles are suspendible in the flow; and thus, if there are not additional sources of coarse material downstream, the annual volume of bedload transport diminishes downstream with distance from the source of coarse material.

Since rock types have different durabilities, the rate of downstream diminution and thus the change in volumetric transport depend on the type of rock from which source materials are derived. For example, a large area of the Olympic Mountains of Washington is composed of basalt, which is by nature easily weathered, and which is mechanically weak because it has been deformed and metamorphosed during the geologic evolution of the Olympic Peninsula. By contrast, granitic rocks found in the headwaters of many western Washington Cascade Range streams, such as the Snohomish River basin, are mineralogically and structurally resistant to breakdown. The nature of geologic materials from which sediment is produced in a river basin thus affects both the quantity and quality of gravel supply to downstream.

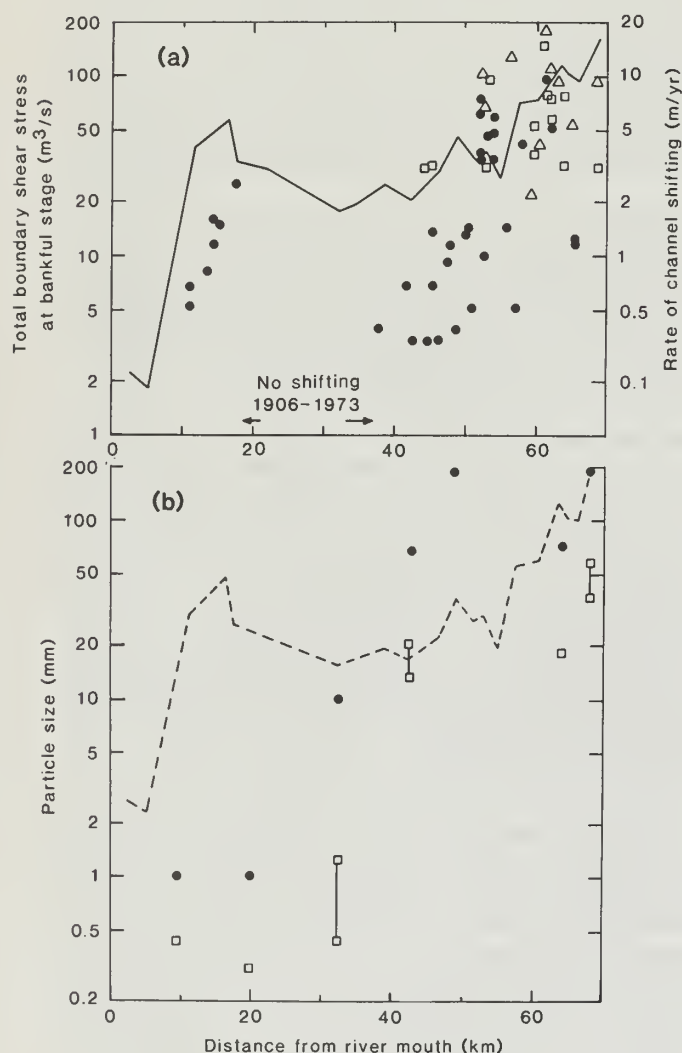


Figure 1. Relation between downstream decreasing transporting ability (dashed line) caused by decreasing gradient, and (a) the rate of channel shifting in the Green River, Washington. Note absence of channel shifting where the transporting ability increases; and (b) maximum particle size that can be transported (solid line), and maximum (circles) and average (squares) particle size found on channel bars.

Downstream Patterns of Sediment Transport, Deposition, and Channel Stability

Many rivers undergo a downstream reduction in gradient in their descent from mountains to lowlands. This reduction in gradient and, therefore, of the river's transporting ability causes the coarse portion of a river's load to be deposited in bars. Where deposition is most rapid and intense, bars are formed in mid-channel as well as along the inside bank of bends (point bars), causing the river channel to braid. Bar deposition in turn diverts the river around the bar toward a bank, causing erosion of the bank and lateral migration of the channel. Figure 1(a) shows the relation between decreasing transporting ability and channel shifting in a typical river draining the west side of the Washington Cascade Range. Areas of rapid bar deposition and lateral channel movement associated with declining gradient are commonly the most intensively used for gravel extraction.

Downstream reduction in gradient is generally accompanied by a reduction in the average grain size of the bedload. This reduction occurs in the absence of downstream sources of coarse particles as the coarsest particles are deposited because of decreasing transporting ability and by the attrition of material from upstream sources. The rate of bedload transport is also reduced with increasing distance from significant sources as attrition converts bedload to suspendible load.

In some cases zones of deposition are characterized by a noticeable building up of sediments on the riverbed (aggradation). This typically results from the combination of a reduced channel gradient and of a large discharge of coarse bed material into the river from sources not far upstream from the depositional zone. Two examples of rivers in which such environments occur (the White River in western Washington and Redwood Creek in northern California) are given as case histories later in this publication. Historical data can be used to determine if a channel is aggrading or degrading at a noticeable rate. The U.S. Geological Survey maintains gages on many rivers, with some of these gages dating to the early twentieth century. By examining the gage height at a chosen low-flow discharge over a period of time, changes in riverbed may be detected (see Case Studies section). Bridge sites can also be useful for detecting changes in bed elevation. A cross-section is generally surveyed at the time of bridge construction; by repeating the survey, net change since the original survey can be determined.

Sampling the riverbed material to determine how the grain-size distribution changes with distance downstream will help to understand the downstream patterns of sediment transport and deposition in a river. Sampling sites at comparable locations along the river must be chosen. Good results have been achieved by sampling near the upper end of the point bar where the maximum rate of sediment transport occurs (Figure 2). The upper several inches of the gravel surface, which is coarser than the underlying material, must be scraped away. Figure 1(b) illustrates the relation between downstream reduction in transporting ability and bed-material particle size in a western Washington river.

Many river basins have undergone or are currently undergoing substantial changes in patterns of sediment production due to land use or to channel modifications. Land uses such as urbanization, agriculture, road construction, and logging usually increase the sediment load of a river, often causing the channel to widen and braid, and aggrade (Madej, 1982). Several other land or channel uses have had widespread consequence in rivers of the western United States, including the construction of upstream impoundments. In general,

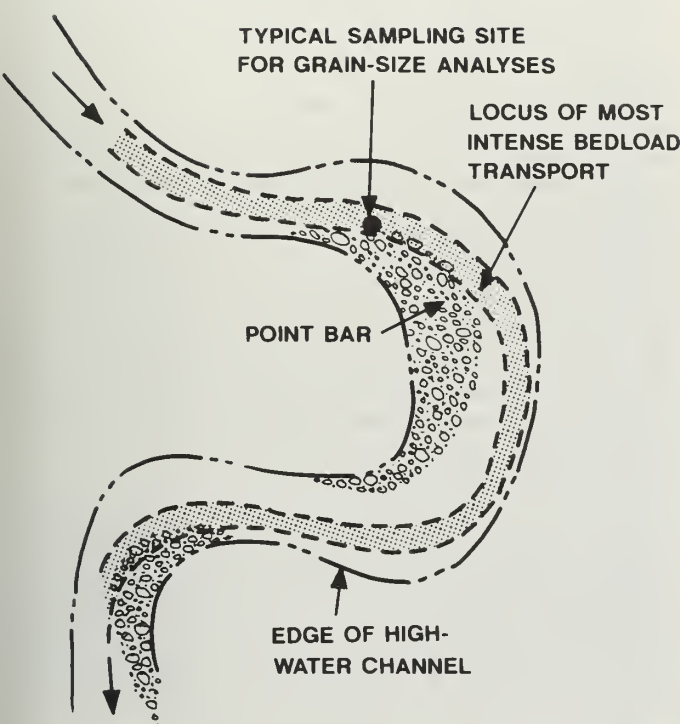


Figure 2. Schematic diagram showing the path of most intense bedload transport through a river bend.

the response of a gravel-bed river to the effects of an upstream impoundment will depend on the severity of modification to flood hydrology, and on the presence or absence of downstream sources of gravel (Milhous, 1982). In the absence of a downstream source of gravel and with only a moderate reduction in flood sizes, the channel can develop a coarser surface (armor), or degrade, or both. On the other hand, if gravel is still contributed to the river below the dam and flood flows are greatly reduced, then gravel may accumulate in the downstream reach.

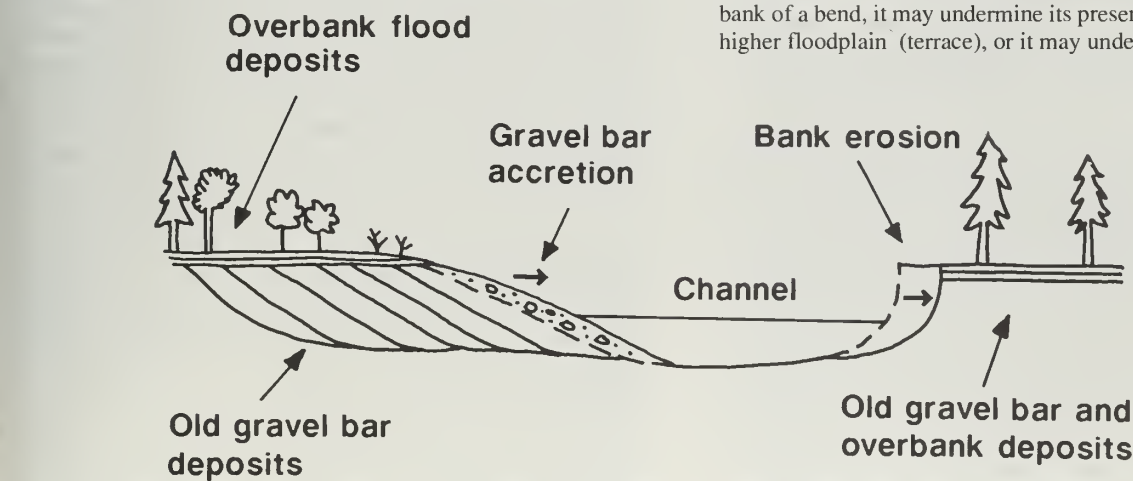


Figure 3. Schematic diagram of lateral channel shifting at a river bend. Accretion of gravel in bars and of fine sediments deposited by floodwaters on the gravel create new floodplains on the inside of the bend. Undermining occurs on the outer bank.

Channelization can also significantly affect the mechanics of river channels. Typical effects of channelization are a shortening of the channel, which results in an increase of the slope, or a narrowing, which results in deeper flows. Both the shortening and narrowing increase the transport ability of the stream. Degradation often results, with the increased sediment load being dropped out (aggrading) downstream where the stream regains its original gradient. In some cases adjustments of bed elevation can persist for many years following channelization (Parker and Andres, 1976; Galay, 1983).

In case of any change to land or channel use that affects sediment production, storage, or transport, at least qualitative statements regarding the magnitude and timing of the resulting effects and their relative importance can be made. Historical materials, such as aerial photos, channel maps and surveys, cross-sections, and flow records, are invaluable sources in determining the effects of various land and channel uses. Sedell and Luchessa (1981) recently showed, with examples from several Oregon and Washington rivers, how a general chronology of land and channel use changes can be constructed back to the mid-nineteenth century using archival materials. Long-term natural influences on river morphology must be separated from the effects of other channel or land uses to assess or predict effects of gravel extraction on river morphology.

Sediment Transport and Geomorphology of Channel Bends

A qualitative understanding of the processes of sediment transport and channel shifting in bends is important for evaluating the potential changes of gravel extraction on adjacent banks and bars.

Most bedload travels along the channel bed and up onto bars on the inside of bends (Figure 2). This accumulation of material on the inside of the bend forces the main thread of the river against the concave, outside channel bank, causing undermining and collapse. Together, the deposition of material on the inner bank and the undermining of the outer bank lead to a lateral shifting of the entire channel without any change of the river cross-sectional form, as shown in Figure 3. As the river moves away from the inner, convex bank, it leaves behind an outward-accreting series of deposits of bed material. Fine sand and silt from the suspended load settle during overbank floods and accumulate on the bed material deposits. The surface becomes colonized by vegetation, the varying age of which often attests to the growth history of the outward accumulation. The surface built up by these processes is called a floodplain. As the river shifts toward the outer bank of a bend, it may undermine its present floodplain, or an older, higher floodplain (terrace), or it may undercut a hillside.

Determining Bedload Transport Rates

Because most of the sand and gravel found in and potentially extracted from the beds and bars of rivers is transported within the bedload, the rate of bedload transport must be known to estimate the rate of replenishment of sand and gravel. There are a number of approaches to determine the transport rate, but not all may be appropriate for a particular river or at a particular location on that river. The various approaches and the considerations governing the usefulness of each are summarized below.

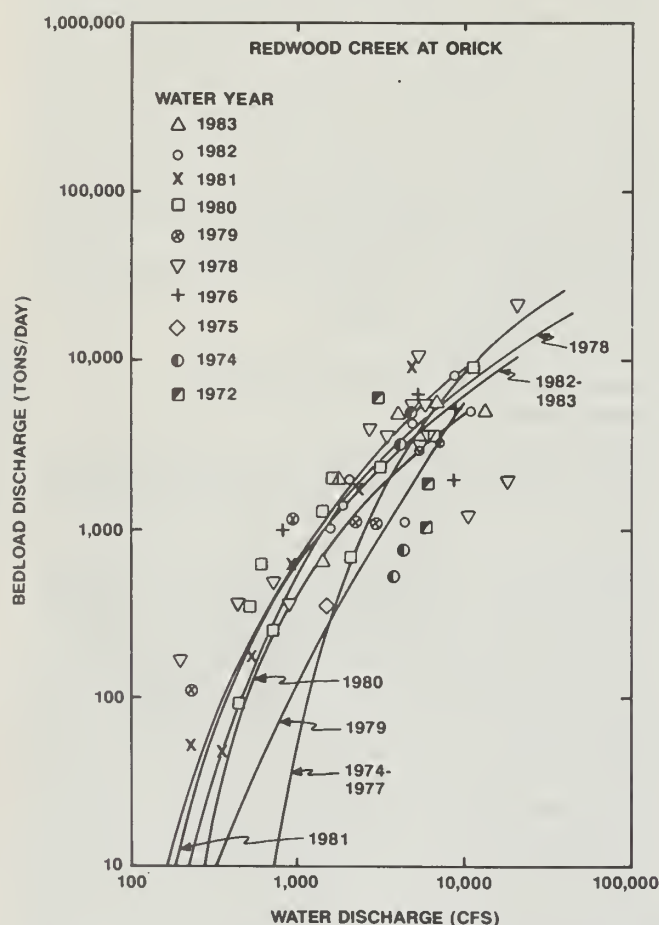


Figure 4. Ten years of bedload transport measurements and rating curves for Redwood Creek near Orick, California. Estimated long-term bedload transport for the period 1954-1980 is 191,000 t/yr, which accounts for 11 percent of the total load.

The first approach is to sample sediment in transport. The standard method of accomplishing this employs a streamlined, weighted collection device known as a Helley-Smith bedload sampler. During a particular flow event, the sampler is lowered to the riverbed for an interval of time at a number of points across the channel. The sampling procedure is repeated during storms of different magnitudes to develop a relation between the transport of bed material and the water discharge. An example of such a relation or rating is shown in Figure 4. The rating is used with flow data to determine instantaneous transport rates, which are summed for all days in a year to estimate annual bedload discharge. Daily flow data are published for gaging stations by the U.S. Geological Survey within Annual Water Resources Data Reports and Water Supply Papers. Because most sediment in gravel-bed rivers is transported during large storms which

occur on the average only several days per year, the rating must be applied to daily flows from at least ten years to adequately determine an average annual sediment discharge. However, for streams draining watersheds smaller than a few tens of square miles, the use of daily average flows causes underestimation of short-term peak discharges and therefore of bedload transport rates.

Several factors limit the usefulness of this approach to estimating transport. Sampling is expensive and requires specialized equipment which is not commonly available. Largely for these reasons, there are at present few bedload transport data from large rivers. Sampling must be carried out over several years to sample high-flow events adequately. Finally, because the greatest sediment transport happens during flows which may not even occur during a several-year measurement period, estimates of transport rates based on extrapolation of the rating curve to storms larger than those sampled produce large errors. For this reason, sampling measurements, while significantly more difficult and expensive to obtain, are often no more precise than estimates obtained using less direct means.

A second approach makes use of various theoretical or empirical bedload transport formulae. Data needed for this approach may often be acquired readily and inexpensively. Data needed include the grain-size distribution of bed material, measured channel cross-sections, the average longitudinal surface slope of the water, and a relation between water depth and discharge. The application of a formula produces a rating curve, which is then used as described above. Each of the available formulae will give reliable results only when variables, such as river slope, depth, and bed-material size, fall within a certain range over which the formula was initially calibrated. For some rivers, particularly those with a very coarse and steep bed, no method may be appropriately applied. However, when variables can be obtained or adequately measured and the conditions satisfied for a particular formula, realistic estimates can be determined for most gravel-transporting rivers. It is always desirable for comparative purposes to use as many formulae as are applicable at a particular location; this is not difficult or time consuming because the formulae all have similar data requirements. Results should always be checked against some independent field evidence.

Bedload typically amounts to a small fraction of the total load of a river. Based on a survey of rivers in which bedload and suspended load have both been measured, general proportional relations between the two have been determined. A third approach to estimating bedload transport makes use of these observations. In nearly all streams the bedload is less than 16 percent of the suspended load, with values of 2-6 percent typical of lowland rivers and of 8-16 percent for mountainous basins (for compilations see: Maddock, in Vanoni, editor, American Society of Civil Engineers, 1975; for examples from Pacific states see: Emmett, 1981; Nelson, 1982; Nelson, 1979; Brown, 1985; Jones and others, 1972). Measured relations between bedload and suspended load are included in the case studies later in this publication for Cache Creek, the Snohomish River, and Redwood Creek. Examples of the application of estimated proportional relations between bedload and suspended load to suspended load measurements are found in the case studies of the Wynnocsee, Satsop, and Russian rivers.

Suspended sediment yield data are available from U.S. Geological Survey publications, scientific journal articles, and other reports. Suspended sediment data are available in many of the larger river basins in the Pacific states, either as separate reports or within Annual

Water Resources Data reports published by the U.S. Geological Survey. The Appendix is a bibliography of sources of large basin sediment data in California, Oregon, and Washington.

In basins for which no suspended sediment transport data are available, estimates may be made of the probable suspended sediment load, based on the range of suspended sediment yields that have been measured from nearby basins with similar characteristics. Inspection of the data published for the far western states indicates that suspended sediment yields fall within definable ranges for different physiographic regions. For example, in rivers draining the Olympic Mountains, suspended sediment loads of 500 to 2,000 t/mi²/yr have been measured; yields range from 1,000-10,000 t/mi²/yr from north coastal California. Yields from river basins in the Puget Lowland and western Cascade Range lie between 100 and 700 t/mi²/yr; river basins draining the eastern Cascade Range average sediment yields of 10-100 t/mi²/yr. These ranges can be narrowed considerably for particular basins within these regions by examining local measured values in comparable basins. The measured sediment yields average conditions over a large area, and include great disparities in rates within an individual basin due to the effects of land use and geologic conditions. Care must be taken in extrapolating suspended sediment yields to consider land use and geologic effects on sediment production in the basin in light of conditions in the basins from which sediment yields are known. Estimating suspended sediment yields for unmeasured basins should be possible within a factor of two to five.

A fourth approach to estimating bedload transport may often be feasible on rivers in which reservoirs are located. Records of deposition may be available directly from the agency responsible for operation of the reservoir in published form (for example, Dendy and Champion, 1978), or in some cases may be determined from measurement. Material deposited within reservoirs includes both bedload and also a significant portion of the suspended load. To derive an estimate of bedload transport, the percentage of the total load entering the reservoir as bedload must be estimated. The portion of the suspended load passing through the reservoir without depositing must also be computed using one of several computational procedures (for example, Graf, 1984). Short-term volumes of bedload can also be obtained from surveys of deposits behind water-diversion dams and other structures which are periodically flushed.

A fifth approach may be feasible in channels undergoing rapid aggradation. A minimum rate of transport through a reach may be computed by measuring rates of aggradation from channel cross-sections at intervals of time (for example: Griffiths, 1979, on the Waimakariri River, New Zealand). The rate is a minimum because it does not account for the portion of the bedload transported through the reach. However, in rapidly aggrading channels, most bedload is often deposited within a relatively short reach, and deposition rates can give reasonable estimates of bedload transport.

A sixth approach makes use of relations between bedload transport and large-scale morphological changes to channels, such as bank erosion or bar accretion. These two processes are more readily measured than is bedload transport. The approach has been successfully used by Neill (1983) in Alaska and Collins and Dunne (1986, 1989) in Washington, who measured rates of bank erosion and bar accretion from sequential aerial photographs, and equated the measurements to bedload transport rates. The estimated value is a minimum, but under certain circumstances closely approximates the

actual value of bedload transport. These approaches have not yet been adequately tested for widespread use, but may be more widely applied in the future.

Estimating long-term rates of bedload transport from rates of gravel extraction alone is not valid because more gravel can be extracted from a river channel than can be replenished from the drainage basin. The difference between extraction and replenishment can be eroded from the river banks or bed (see Case Studies section). However, if in addition to extraction rates, cross-section changes are available, the transport rate from upstream into the reach may be estimated as illustrated in several of the case studies below.

In summary, no single approach to estimating bedload transport is best suited to all rivers, nor is any one method likely to be absolutely reliable. Whenever possible, several independent methods should be used. If methods are used under appropriate conditions, an estimate of bedload transport in a given river to within a factor of at most two to five will always be possible. This level of accuracy is often adequate for river-channel management purposes.

MANAGEMENT OF GRAVEL EXTRACTION EFFECTS

The following text summarizes how knowledge developed about the dynamics of a particular river may be incorporated into a program of gravel-mining management.

- (1) Appropriate rates and locations of gravel extraction should be determined, based on:
 - (a) The rate of replenishment from upstream.
 - (b) Whether the river bed elevation under undisturbed conditions remains unchanged over the course of decades, or if not, the rate at which it is aggrading or degrading.
 - (c) Historical patterns of sediment transport, bar growth, and bank erosion in particular bends.
 - (d) Prediction of the specific, local effects of gravel extraction on bed elevations, and the stability of banks and bars. When possible, the prediction should take into account an analysis of present or past effects of gravel mining at various rates.
 - (e) A determination of the desirability or acceptability of anticipated effects.
- (2) Records of gravel extraction volumes should be maintained.
- (3) Following the implementation of a regulated gravel extraction rate, it may be desirable to establish a monitoring program. The program may be simple and inexpensive if carefully designed. To monitor changes in bed elevation, channel cross-sections may be used. Monitoring upstream and downstream of the immediate vicinity of a bar operation is a necessity because effects can extend upstream and downstream. At a minimum, cross-sections should be located at riffles immediately upstream and downstream of a mined bar. Aerial photographs are a powerful tool for evaluating the rates of lateral migration of a river. Aerial photographs of a suitable scale are typically taken at regular intervals in most areas by state and local agencies.
- (4) Permitted extraction quantities should be periodically reviewed in light of the results of the monitoring program, or as improved estimates of replenishment become available.

The status of planning efforts in several rivers in which gravel extraction effects have been identified are included in the case studies presented below.

CASE STUDIES

The following eight case studies illustrate how gravel extraction effects have been or are currently being analyzed and managed. The case studies are organized as follows. First, rivers are described in which the bed elevation under undisturbed conditions is stable over periods of decades, but in which degradation has occurred in response to gravel mining. These are represented by: the Humptulips, Wynoochee, and Satsop rivers in Washington; the Russian River and Cache Creek in California; and the Manawatu River in New Zealand. An example is also included of an intermittent, southern California river in which a gravel pit caused catastrophic degradation during a flood (Tujunga Wash). These cases are followed by two streams (the White River in Washington and Redwood Creek in California) in geologic environments that favor long-term aggradation, and in which gravel extraction has been used to slow aggradation or to stabilize the bed elevation. The final study documents effects to bars and banks downstream and adjacent to mined bars (Skykomish River, Washington).

Humptulips, Wynoochee, and Satsop Rivers, Washington

The study described below (Collins and Dunne, 1986; 1989) was commissioned by the Grays Harbor County Planning Department at the request of the county Shoreline Hearings Board, an agency responsible for issuing one of the permits required to remove gravel from the county rivers. Because the Humptulips, Wynoochee, and Satsop are salmon-spawning rivers, concern was expressed about whether gravel-bar mining may have been limiting the supply of gravel for spawning. The study described below was designed to

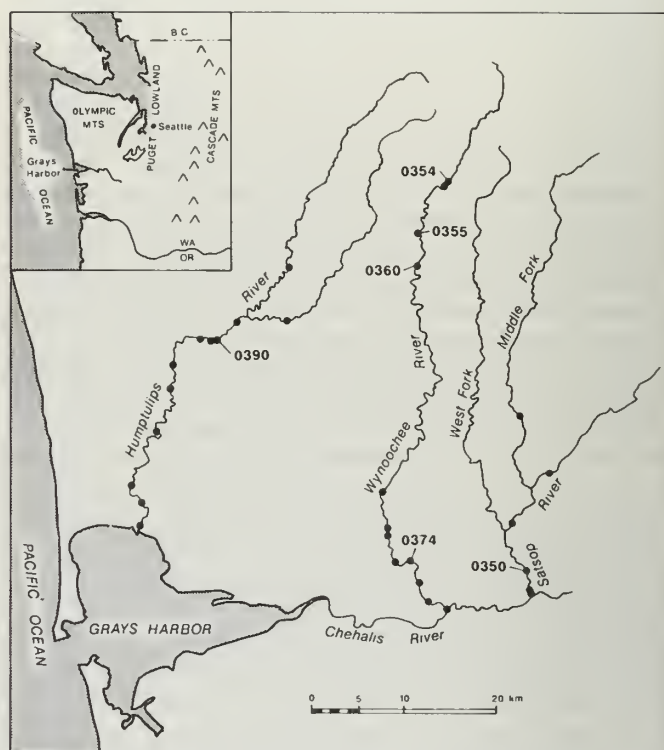


Figure 5. Location of the Humptulips, Wynoochee, and Satsop rivers, Washington, and locations of bed-material sample sites (Figure 6) and gages (Figure 8).

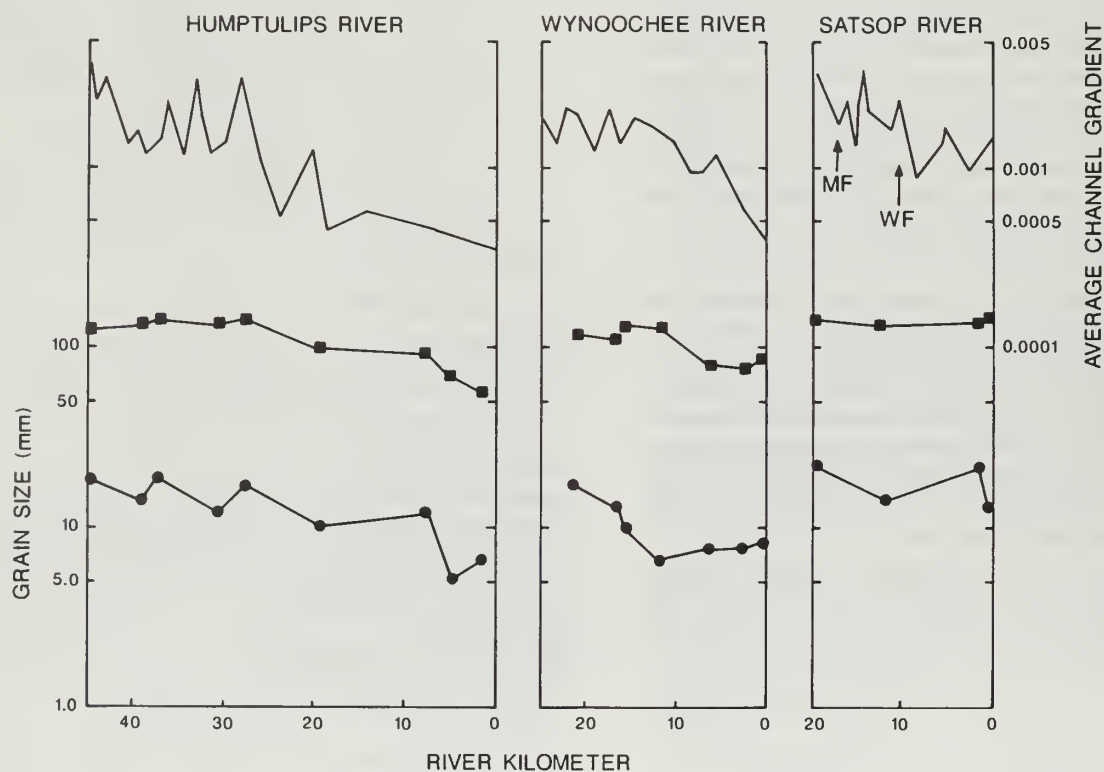


Figure 6. Variation along the Humptulips, Wynoochee, and Satsop rivers of the average channel gradient, the median diameter of riverbed material (circles), and of the average of the diameters of the six largest particles undergoing frequent transport, as indicated by their positions, orientations, clean surfaces, and relation to flotsam and other particles (squares).

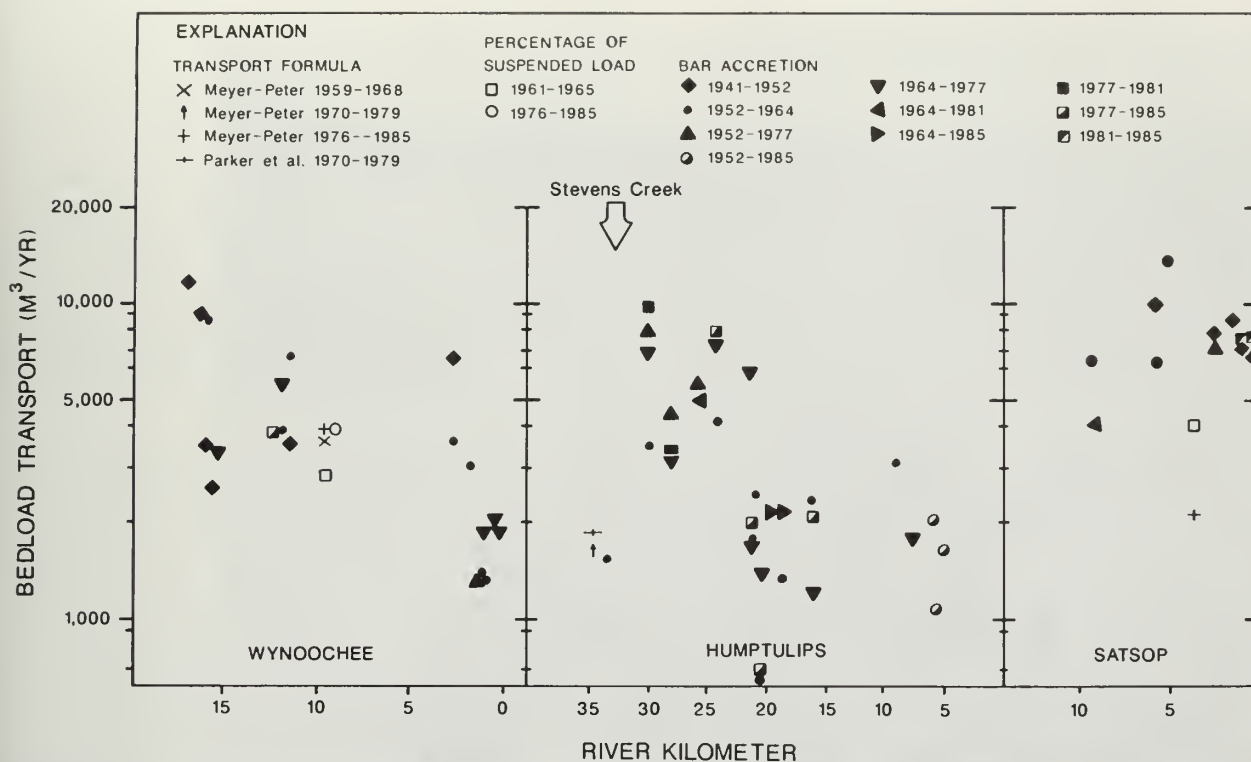


Figure 7. Average annual volumetric bedload transport along the Humptulips, Wynoochee, and Satsop rivers, as estimated from two transport formulae, percentage of suspended load, and bar accretion rates.

determine the supply of gravel rapidly and inexpensively; it also documented changes to bed elevation caused by gravel extraction in excess of supply.

The Humptulips, Wynoochee, and Satsop rivers (Figure 5) originate in the steep southern Olympic Mountains, where they are supplied by landsliding and soil creep with colluvium derived from the basaltic bedrock, and with fine sediments from surface erosion of gravel-surfaced roads, landslide scars, and other locally disturbed sites. The Humptulips and Wynoochee rivers then flow through thick deposits of gravel and sand transported by meltwater from alpine glaciers that originated in the Olympic Mountains and that last extended downvalley about 18,000-13,000 years ago. Gravel terraces in the lower reach of the Satsop River originated from the Puget Lobe of the continental ice sheet, and therefore contain more resistant crystalline rocks from the northern Cascade Range and Canada. In these reaches all three rivers are supplied with coarse bed material by lateral erosion of the meltwater deposits (terraces).

The three rivers -- the Humptulips, Wynoochee, and Satsop rivers -- undergo marked reduction in gradient and bed-material grain size in their lower 45, 15, and 10 kilometers, respectively (Figure 6). These reaches of declining gradient and transporting ability are therefore the sites of rapid deposition in the form of large bars. Basaltic source materials in the Humptulips and Wynoochee rivers are mechanically weak and are subject to attrition during transport. A significant reduction in particle size was induced during laboratory experiments in which river transport was simulated, with a 40 percent weight loss among particles coarser than 0.5 millimeter during approximately 26

kilometers of simulated transport. The attrition rate was less for a sample of outwash from the Satsop River drainage. In the river environment the rate would be considerably greater due to the effects of weathering of gravel stored in floodplains. Because of downstream attrition, the absence of significant sources of coarse sediment in the lower reaches, and deposition and storage in response to declining gradient, the transport rate of gravel is expected to decline gradually downstream.

Transport rates were estimated using three independent methods and the results compared. In the first method, bedload was estimated as four percent of the suspended sediment load sampled over a three-year period in the Wynoochee and Satsop rivers (Glancy, 1971). The percentage was transferred from results of simultaneous measurements of bedload and suspended load in the Soleduck and Bogachiel rivers (Nelson, 1982), western Olympic Mountain rivers having similar geologic and hydrologic conditions. A second estimate was made using two bedload transport formulae calibrated for gravel of the appropriate texture. A third estimate was derived by mapping rates of bar accretion on six sets of aerial photographs from the period between 1941 and 1985, and converting those areas to volumes on the basis of field-measured bar heights. Results of the various methods were in agreement (Figure 7), and confirmed the expected pattern of downstream decreasing bedload transport. Figure 7 indicates that in the Humptulips River, transport is about 1,900 m³/yr (2,500 yd³/yr) upstream of Stevens Creek. Downstream of the influx of gravel from Stevens Creek at river kilometer (Rkm) 36, about 5,000 m³/yr (6,500 yd³/yr) are transported. In the absence of additional sediment sources,



Photo 1. Satsop River near Satsop, Washington.

this rate decreases to about $2,300 \text{ m}^3/\text{yr}$ ($3,000 \text{ yd}^3/\text{yr}$) at Rkm 24, and about $1,500 \text{ m}^3/\text{yr}$ ($2,000 \text{ yd}^3/\text{yr}$) at Rkm 8. The Wynoochee River annually transports about $7,000 \text{ m}^3/\text{yr}$ ($9,000 \text{ yd}^3/\text{yr}$) past Rkm 16, $4,000 \text{ m}^3/\text{yr}$ ($5,000 \text{ yd}^3/\text{yr}$) past Rkm 9, and about $3,000 \text{ m}^3/\text{yr}$ ($4,000 \text{ yd}^3/\text{yr}$) past Rkm 5. The flux of bedload through the short (10-km long) mainstem of the Satsop River (Photo 1) is relatively constant at about $8,000 \text{ m}^3/\text{yr}$ ($10,000 \text{ yd}^3/\text{yr}$).

Minimum rates of gravel extraction, which is limited to sub-aerial bars, were documented by totaling incomplete records from gravel extraction operations. Informal information allowed for a more full account of extraction. It was found that even the lower, minimum rate was several times greater than the computed replenishment rate, and that the higher, estimated value was as much as ten times greater.

To reconcile the conflicting estimates of replenishment and offtake, records of bed elevation and width were examined, since the channel margins could have been potential sources for the "missing" gravel. Inspection of six sets of aerial photographs taken over a 44-year period showed no change in river width. Two sources of data were available on riverbed elevation. Data from U.S. Geological Survey gages were available from eight sites on the two rivers. Inspection of annual trends in the gage heights at a common discharge showed systematic degradation at some of the gages (Figure 8). On the Humptulips River, degradation was apparent on the one gage from the earliest year, 1932, from which data were available to the time of its abandonment in 1979. On the Wynoochee River, degradation was apparent on a gage in the downstream reach at Rkm 9 since 1966. A dam built upstream in 1972 would not be expected to have caused the

degradation because the greatest sources of sediment are downstream of the dam and because the dam is far upstream from the degrading reach. Moreover, the dam could not have caused the degradation because it was not built until six years after the degradation began and because of the absence of degradation at a gage located in an alluvial reach upstream at Rkm 65, nearer to the dam (Rkm 83). By examining the gravel extraction records, it was determined that the onset and inter-annual variations in amount of degradation matched the onset and changes in volumes of gravel extraction. Rates of degradation at the gage sites were confirmed by obtaining cross-sectional profiles from bridge sites downstream from the gages on the two rivers and resurveying them in 1986.

A computation was then made of the amount of gravel removed from the channels by degradation by applying the average degradation rates measured at the gage sites to the areal extent of streambed in the reaches subject to gravel extraction. On the Wynoochee River, $380,000 \text{ m}^3$ ($500,000 \text{ yd}^3$) was removed by degradation in a 19-year period between Rkm 3 and 18. Documented gravel offtake during this period minus the 19-year gravel supply is $(470,000 \text{ m}^3 - 73,000 \text{ m}^3 = 400,000 \text{ m}^3)$ ($620,000 - 95,000 \text{ yd}^3 = 530,000 \text{ yd}^3$), a value agreeing closely to the $380,000 \text{ m}^3$ ($500,000 \text{ yd}^3$) figure for channel-bed degradation. A similar computation was made for the Humptulips River between Rkm 26 and Rkm 45, showing bed degradation of $600,000 \text{ m}^3$ ($800,000 \text{ yd}^3$) over a period of 25 years. The estimated offtake rate was $760,000 \text{ m}^3$ ($1,000,000 \text{ yd}^3$). Subtracting the replenishment, about $77,000 \text{ m}^3$ ($100,000 \text{ yd}^3$), again approximately balances the degradation volumes and indirectly confirms the previously estimated replenishment rates.

Following completion of the study in June 1986, the Shoreline Hearing Board in January 1987 recommended that gravel extraction be allowed only for the purposes of erosion control, enhancement of fish and wildlife habitat, and use by property owners. The County Commissioners held several public hearings from January through May 1987 during which a policy was developed, based on the Board's recommendation and public and agency comment and discussion at the hearings. The policy stipulates that mining be allowed until 1990 in each of the three rivers, with total offtake in the Wynoochee and Satsop rivers to be reduced in annual steps to 4,000 m³/yr (5,000 yd³/yr), the replenishment rate at Rkm9, and 8,000 m³/y (10,000 yd³/yr), the rate through the mined reach, respectively in 1990. In the Hump-tulips River, extraction of 19,000 m³/yr (25,000 yd³/yr) is to be allowed until 1990, and a study is to be conducted during this time on the effects of gravel extraction on river ecology.

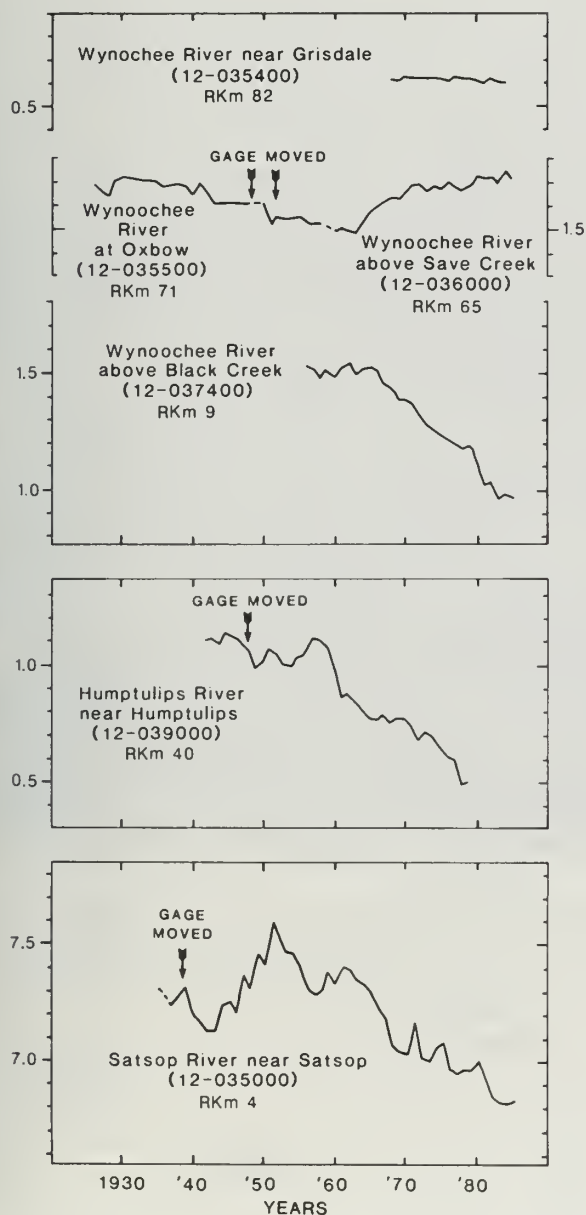


Figure 8. Mean annual water surface elevations at a flow of 14 m³/sec at U.S. Geological Survey gages on the Humpulips, Wynoochee, and Satsop rivers.

Lower Manawatu River, New Zealand

A simple mass balance approach was also used on the Lower Manawatu River (Page and Heerdegen, 1985) to assess historic and present effects of gravel extraction on bed elevations and banks. The Manawatu River drains 2,300 square miles of New Zealand's North Island (Figure 9). Downstream of the confluence of the Pohangina River, a major tributary, the river is known as the Lower Manawatu River and consists of two distinct reaches. Upstream of Poka Poka Point (Figure 9), the low-sinuosity channel is characterized by coarse-grained bedload gravels. Downstream an abrupt change to a highly sinuous channel formed in fine sands and silts occurs. This change corresponds to a marked reduction in gradient in the lower reach relative to the upper reach. The topography is explained by the recent geologic history of the river. By 6,000 years ago the maximum post-glacial sea level converted the Lower Manawatu River valley downstream of about Poka Poka Point into an estuary which acted as a sink for fine-grained sediment. Fluvial deposition in the last 6,000 years eventually created a low-gradient, deltaic plain across which the river presently flows through a series of tortuous bends.

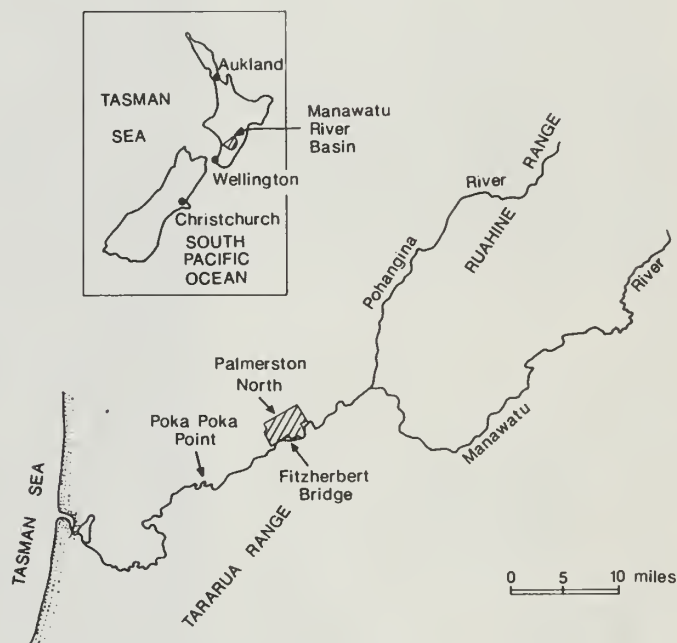


Figure 9. Location of the Lower Manawatu River, New Zealand.

Analysis of historical surveys, channel maps, and aerial photos indicated that this upper, wider, steeper, and less-sinuosity, gravelly reach has been extending progressively farther downstream during the past several centuries. This modification appeared to have stopped or slowed in about 1965. The stabilization of the channel is thought to be caused in part by bank protection works which were initiated at that time.

The channel has also undergone recent bed degradation. Gravel has been removed from various locations in the channel since the 1900s. Rates are documented for the 20-year period leading up to 1985 during which time five million cubic yards have been removed, or about 250,000 yd³/yr, if it is assumed that extraction has occurred at a steady pace. The replenishment rate is estimated to be 100,000 to 130,000 yd³/yr, an amount about one-third to one-half the estimated

offtake rate. The report by Page and Heerdegen (1985) does not indicate how the replenishment rate was derived. Extraction occurs over a 23-mile long reach extending from a short distance below the Pohangina and Manawatu rivers confluence to Poka Poka Point (Figure 9), with an average channel width of 160 yards. A total bed area of 6.8×10^6 square yards is therefore subject to degradation. Subtracting the estimated replenishment rate from the offtake rate and applying it to the affected area of streambed indicates that 1.2-1.4 feet of degradation could be expected to have occurred.

A check on this prediction was made by the repeated survey of channel cross-sections. In 1967 the Manawatu Catchment Board surveyed cross-sections every one mile along the river. The sections were resurveyed in 1976. On average, the cross sections indicated a degradation of 0.8 feet over nine years. Maintenance of this rate for 20 years would result in 1.7 feet of net degradation, a value which agrees reasonably with the 1.2-1.4 feet predicted above on the basis of a comparison of transport and offtake rates.

A further check was provided by examining changes in the discharge rating curve at two stream gages in the Palmerston North area. At Fitzherbert Bridge (Figure 9), data are available for the period 1929 to 1977. Figure 10 shows a period of rapid degradation between 1964 and 1977 when the bed was lowered by approximately 3.3 feet. Although it is not shown in the figure, only minor fluctuations occurred prior to 1950. At a second gage site, Ruahine Street, records begin in 1972. Here the period of degradation is replicated with about 1.5 feet of degradation in the period 1972 to 1977. Taken together the two records are consistent with a decline in mean bed elevation in the vicinity of the city of a little over 3.3 feet in the past 10 years. Because the gage data are from single locations, they do not indicate degrada-

tion rates equal to those averaged from the twenty cross sections, but they independently confirm that degradation is occurring.

The Manawatu Catchment Board has instituted a monitoring plan for gravel extraction; details could not be obtained for inclusion in the case study.

Cache Creek, California

The following summary illustrates dramatic rates of bed degradation (up to 27 feet over a 21-year period) resulting from gravel extraction, which has greatly exceeded replenishment during most of this century. Because the amount of degradation is so great, several consequences of bed lowering are well illustrated: effects on groundwater levels in floodplains, consequences for overbank flooding, and effects on bridges.

Cache Creek, originating on the east slope of the Coast Range of northern California and ending in the Sacramento Valley near Sacramento (Figure 11), drains an area of 1,150 square miles. About one-half (572 square miles) of the Cache Creek basin drains into Clear Lake, which collects sediment from the upper drainage basin. Below Clear Lake, Cache Creek descends steeply through a canyon to a narrow alluvial valley in which the gradient drops. This valley broadens near Capay (Figure 11). Downstream from Capay, the gradient continues to decline, from 0.0027 near Capay to 0.00095 near Yolo, with an intervening section which steepens to 0.0040 where bedrock now crops out in the streambed. Alluvium in this lower valley downstream of Capay is generally 50-160 feet thick, reaching up to 200 feet west of an outcropping of the underlying bedrock about halfway between Capay and Yolo, and up to 300 feet thick to the east.

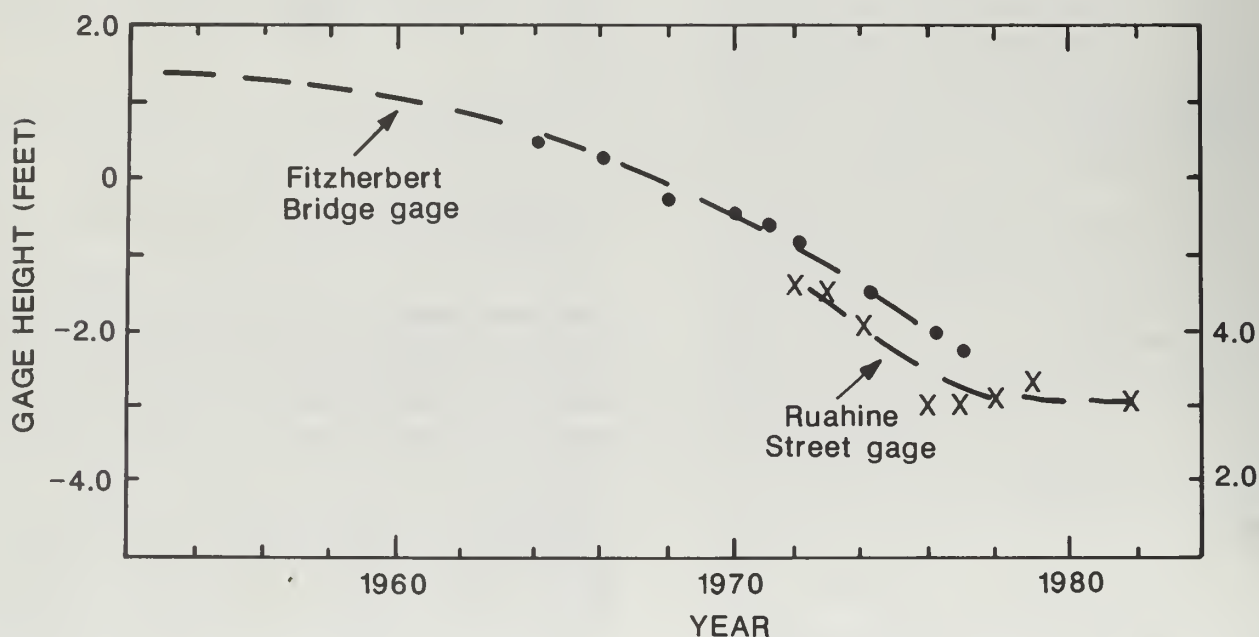


Figure 10. Changes in stage for a discharge of 500 cfs at two gages in the Manawatu River near Palmerston North, 1952-1982. (Figure redrawn from Page and Heerdegen, 1985).



Photo 2. Cache Creek looking upstream between Capay and Yolo. The channel is extensively mined between levees; mining has caused the streambed to lower by 20 to 30 feet. Bridge in middle ground was redesigned in 1981 to compensate for bed lowering, which undermined bridge supports.

Most of the bedload carried by Cache Creek is deposited within the 14.5-mile long reach between Capay and Yolo. This reach is the location of intense braiding and channel shifting and has also been the site of intensive gravel extraction since at least the 1930s, and probably since the turn of the century (Environ, 1980) (Photo 2). Construction of a diversion dam near Capay and subsequent irrigation diversions in 1912 caused the streambed to be seasonally dry, allowing in-channel sand and gravel extraction during the summer season.

Cache Creek drains highly erodible terrain with many mechanically weak and easily erodible rocks within the watershed. The rate of bedload transport for the reach has been computed by the U.S. Geological Survey, based on data collected between 1958 and 1967 (Jones and others, 1972). Jones and others collected samples of bed material from Cache Creek at a gage near Yolo (Figure 11), which they used in a bedload transport formula. The bed composition is dominated by fine gravel and very coarse sand, with a median grain

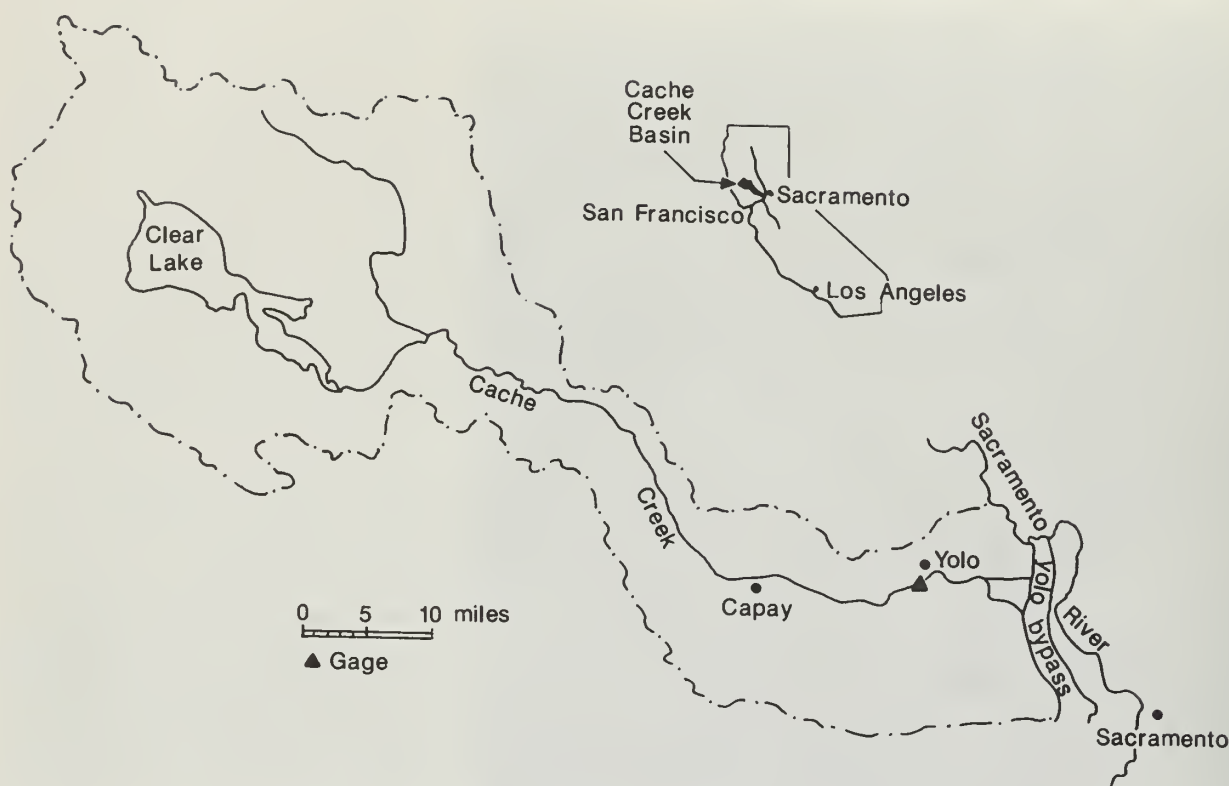


Figure 11. Location of the Cache Creek drainage basin, California.

size of 3.2 millimeters. Jones and others computed a bedload transport of 77,000 t/yr, which represents six percent of the suspended load. Transport has not been computed for the upstream end of the reach and is probably significantly greater.

Prodigious quantities of sand and gravel have been extracted from the creek channel. Approximate quantities are available for the period prior to 1976, with exact production figures available since that time. Prior to 1950, about 300,000 t/yr were extracted. This figure rose to about 900,000 t/yr between 1951 and 1957, to 2,000,000 t/yr between 1957 and 1970, 2,300,000 t/yr between 1970 and 1975, and 2,600,000 t/yr between 1976 and 1986. Production peaked at 4,700,000 tons in 1978. About 80 to 90 million tons of sand and gravel has been extracted from the 14.5-mile long reach since significant mining began. Figure 12 shows the cumulative production of sand and gravel from Cache Creek, indicated by the above rates, and assuming that the 300,000 t/yr figure can be extended back from 1950 to at least 1905.

Longitudinal thalweg profiles of Cache Creek from 1959 and 1980 indicate an average lowering of 15 feet over the 21-year period. Figure 13 shows the change in bed elevation with time at the Yolo gage, which is located one mile below the most downstream operation, and, therefore, does not show a rate of lowering as rapid as farther upstream. The figure indicates that prior to 1947 the bed lowered on average 0.04 ft/yr. From 1947 to 1967 the rate increased to about 0.27 ft/yr. The rate increases in the late 1960s, and subsequently slows in the late 1970s and early 1980s, maintaining the same overall average rate of lowering between 1967 and 1984 as between 1947 and 1967.

There is a strong correspondence between the cumulative extraction shown in Figure 12 and the cumulative lowering shown in Figure 13. Volumetric degradation between 1952 and 1974, computed from longitudinal profiles and aerial photographs, indicated a volumetric change of 48 million tons (Woodward-Clyde Consultants, 1976). This compares reasonably to the total offtake of 43 million tons indicated by the approximate production quantities available for that period. Both figures are much greater than the 1.7 million tons Jones and others (1972) data indicate would have been transported during the same period at the lower end of the reach. While with the available data an exact budget of transport, extraction, and degradation cannot be made, it is clear that the replenishment rate is very small relative to the similar offtake and degradation amounts.

There have been several obvious effects of the rapid bed lowering. All of the bridges between Capay and Yolo have been undermined to some degree (Environ, 1980). The flood capacity has been increased by an estimated 50,000-100,000 cfs (Woodward-Clyde Consultants, 1976). This increase in capacity exceeds the maximum flood measured during the previous 80-year period of record of 41,400 cfs, suggesting that the potential for future overbank flooding has been eliminated.

The streambed lowering has had two other consequences. Groundwater levels have dropped in the lower Cache Creek basin due to groundwater overdraft. As a result of the drop in the groundwater table, the upper segment of the mined reach of Cache Creek has changed from a drain to a source of groundwater recharge. The lower

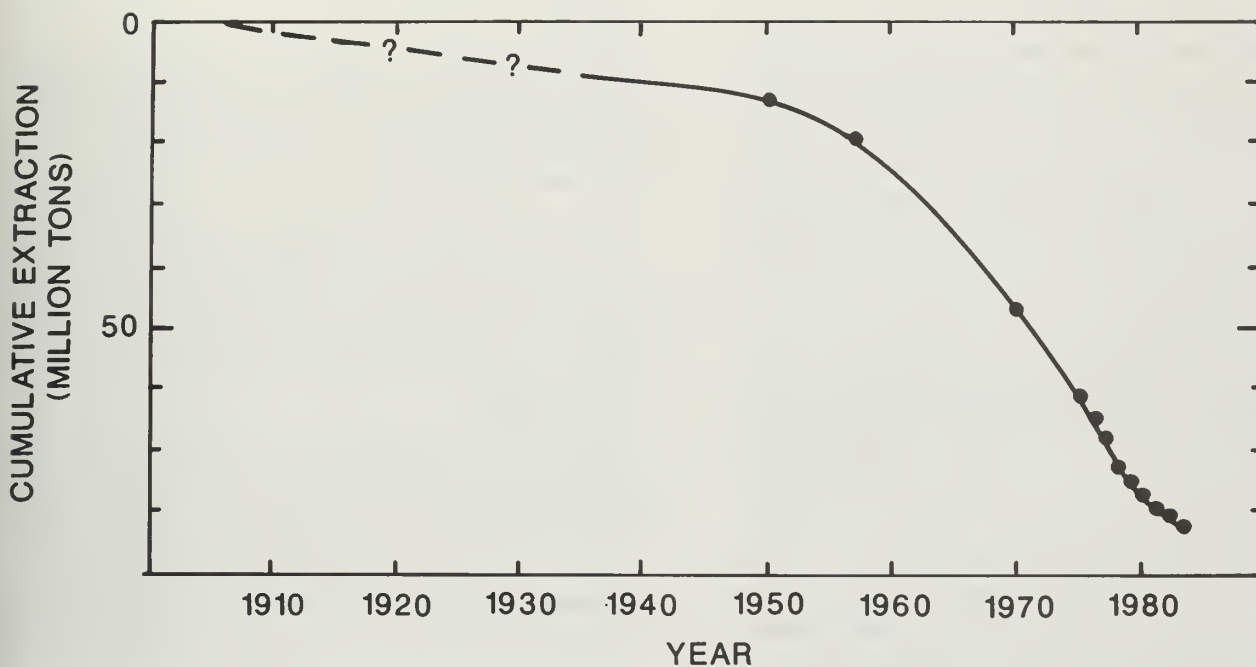


Figure 12. Cumulative annual volumetric gravel extraction, 1905-1986, in Cache Creek from Capay to Yolo.

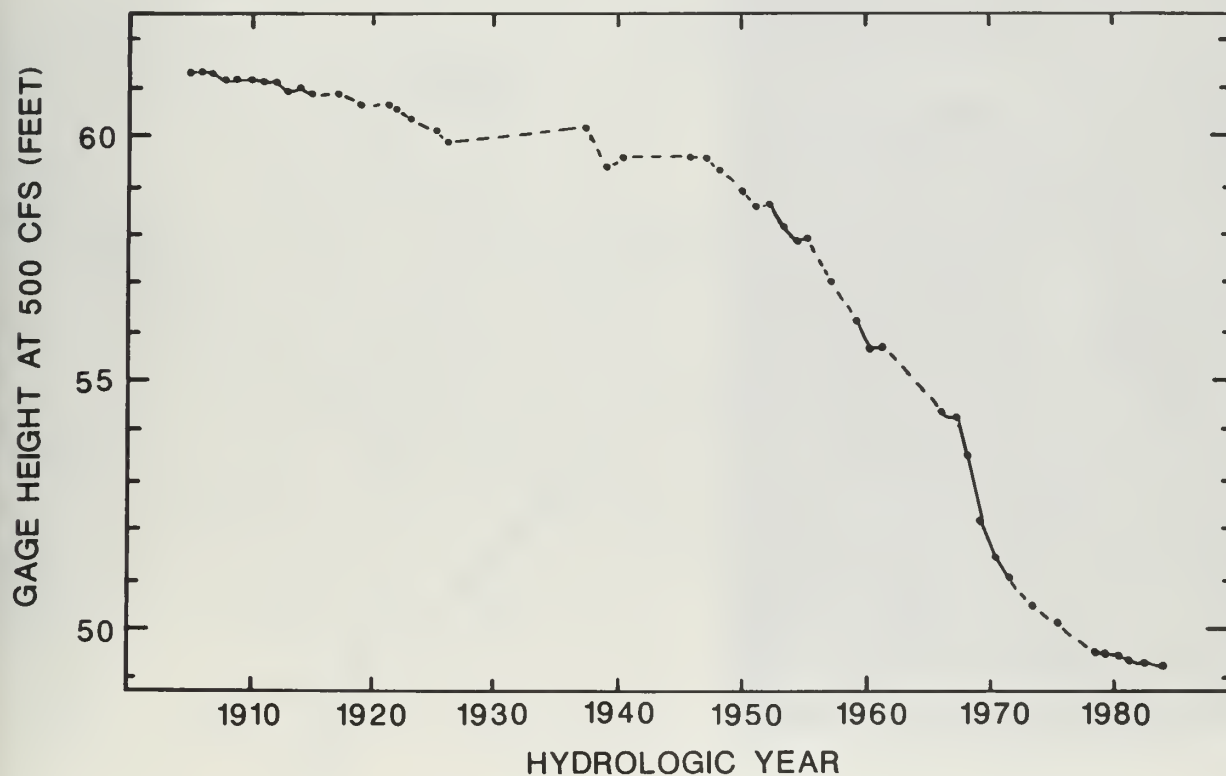


Figure 13. Water-surface elevation at a discharge of 500 cfs at the Cache-Creek-near-Yolo gage, 1905-1984.

segment is still a zone of groundwater discharge (groundwater drains to the creek). In this lower reach, streambed lowering has caused a loss in aquifer storage potential, but the amount due to the creek-bed lowering as opposed to the regional drop in groundwater tables is unclear (Environ, 1980; Wahler Associates, 1981).

Net widening of the stream channel during the period of intensive sand and gravel extraction is not apparent. Woodward-Clyde Consultants (1976) compared the areas of active erosion and deposition on aerial photographs from 1939 and 1972, and documented a decrease of 73 acres (0.11 square miles) in the area of active streambed, indicating a net narrowing of the channel. However, they indicate that, as previously described in this publication, newly accreted floodplain will not be subject to regular inundation by floodwaters and deposition of fine, organic rich sediments. Thus, while no net widening has occurred, the newly accreted land will not evolve soil properties comparable to the land lost during channel migration.

In 1975 Yolo County formed an Aggregate Resources Committee, which commissioned a study the following year in which the impacts of sand and gravel extraction were identified. In 1977 they concluded that the long-range management objectives were to minimize loss of land, minimize flooding, protect or enhance groundwater supplies, and maintain or enhance the agricultural industry. In 1979, extraction was regulated by several interim ordinances. Provisions of the ordinances included the restriction of mining below the estimated 1978 thalweg elevation and the reporting of gravel extraction quantities. The quantity of sand and gravel extracted was regulated by limiting

each operator to annual removals no greater than the amounts extracted during 1976, 1977, or 1978, which represents a maximum allowable rate of 4.4 million tons per year. Annual topographic mapping of the riverbed was initiated in 1983; the information is currently being analyzed. A long-term management plan has not yet been developed.

Effects similar to many of those in Cache Creek have also been documented in the Santa Clara River, a sand-bedded stream that drains the Transverse Ranges of south coastal California. Details may be found in a report by Simons, Li & Associates (1983).

Russian River, California

The following summary reiterates several points illustrated by the Cache Creek case study. Similar to Cache Creek, the Russian River has undergone significant rates of degradation as a result of gravel extraction, with local lowering of 18 feet between 1940 and 1972. As evidenced by the Cache Creek case, the Russian River illustrates the use of streambed survey data to document the rate and indicate the cause of degradation.

The Russian River drains 1,485 square miles of north coastal California (Figure 14). Sediment yields in the Coast Range are high, due in part to the deeply sheared and fractured, clay-rich rocks, which favor the occurrence of slump-earthflows. Intensive grazing of hills and lowland farming also favor surface erosion. Suspended sediment yields measured in the Russian River near Guerneville (Figure 15) are about 1,000 t/mi²/yr.



Photo 3. Russian River looking downstream from Dry Creek confluence; Dry Creek visible entering from lower right corner. Both the channel and the adjacent terrace have been mined; lakes on right are from recent mining.



Figure 14. Location of the Russian River basin, California.

The lower Russian River valley is filled with deep deposits of alluvium which were laid down when sea levels began to rise following the last glacial period about 20,000 years ago. Three areas in the lower Russian River have been important sources of sand and gravel: the "middle reach" extending downstream of Healdsburg to about river mile (RM) 20; the Alexander Valley reach between Healdsburg and Cloverdale; and Dry Creek, a tributary to the Russian River at RM 30.7 (Photo 3). A canyon reach of the Russian River separates the lower basin from an upper alluvial basin near Ukiah. While gravel has also been extensively mined in the upper basin, the most detailed data on extraction and on changes to river morphology have been assembled for the middle reach and Dry Creek in the lower basin. These areas will be the focus of this discussion.

Bedload transport was estimated for the Russian River in a study conducted by the Sonoma County Water Agency (1972) under the supervision of H.A. Einstein. In this study, transport was estimated by measuring the downstream movement of gravel bars from sequential aerial photographs, and by converting the areal change to a volume by use of field-measured channel cross-sections. The rate determined in this way was 39,000 yd³/yr (57,000 t/yr) upstream of Healdsburg. An estimate was made that due to the effects of particle attrition and deposition on the bed about one-fourth or 14,000 t/yr of the 57,000 t/yr would be transported through the middle reach below Healdsburg.

A second estimate of bedload transport can be made from suspended sediment data collected at a U.S. Geological Survey gage between Healdsburg and Guerneville (RM 19). At this site, the measured suspended sediment yield between 1977 and 1986 averaged 1,100,000 t/yr. Because the channel and bed characteristics of the Russian River at the Guerneville gage are similar to the characteristics

of Cache Creek near the sediment measurements discussed in the Cache Creek case study, the same proportional relation between bedload and suspended load determined for Cache Creek may be assumed to apply to the Russian River. Applying the six percent figure determined from measurement in Cache Creek to 1,100,000 t/yr indicates an annual transport of 66,000 t/yr (45,000 yd³/yr).

A third indication of the annual flux of bedload is provided by measurements of bedload transport made by the U.S. Geological Survey in water years 1985 and 1986. Annual rates, published in the 1985 and 1986 Water Resources Data reports for California, were 15,000 t/yr and 98,000 t/yr, respectively, or an average of 56,000 t/yr. Suspended sediment transport for these two years averaged 1,200,000 t/yr, or close to the 1977-1986 average of 1,100,000 t/yr. Because the 1985-1986 suspended sediment rate is close to the 1977-1986 suspended sediment rate, the 56,000 t/yr bedload average for 1985-1986 may be assumed to be a good estimate of long-term bedload transport. Measured bedload was five percent of suspended load during 1985-1986, which compares well with the six percent figure transferred from Cache Creek, and suggests that the approach used to estimate bedload as a percentage of suspended load gave a reliable result in this particular application.

Changes in stream channel cross-sections have been measured at various times and locations on the middle reach. Of those available, the most extensive surveys were made by the U.S. Army Corps of Engineers in 1940 and 1972. Longitudinal profiles from thalweg elevations at the cross-sections (Figure 15) indicate a drop in bed elevations between 1940 and 1972 averaging 11.5 feet, with a maximum of 18 feet. The degradation indicated by Figure 15 represents a volume of about 10 million tons between 1940 and 1972.

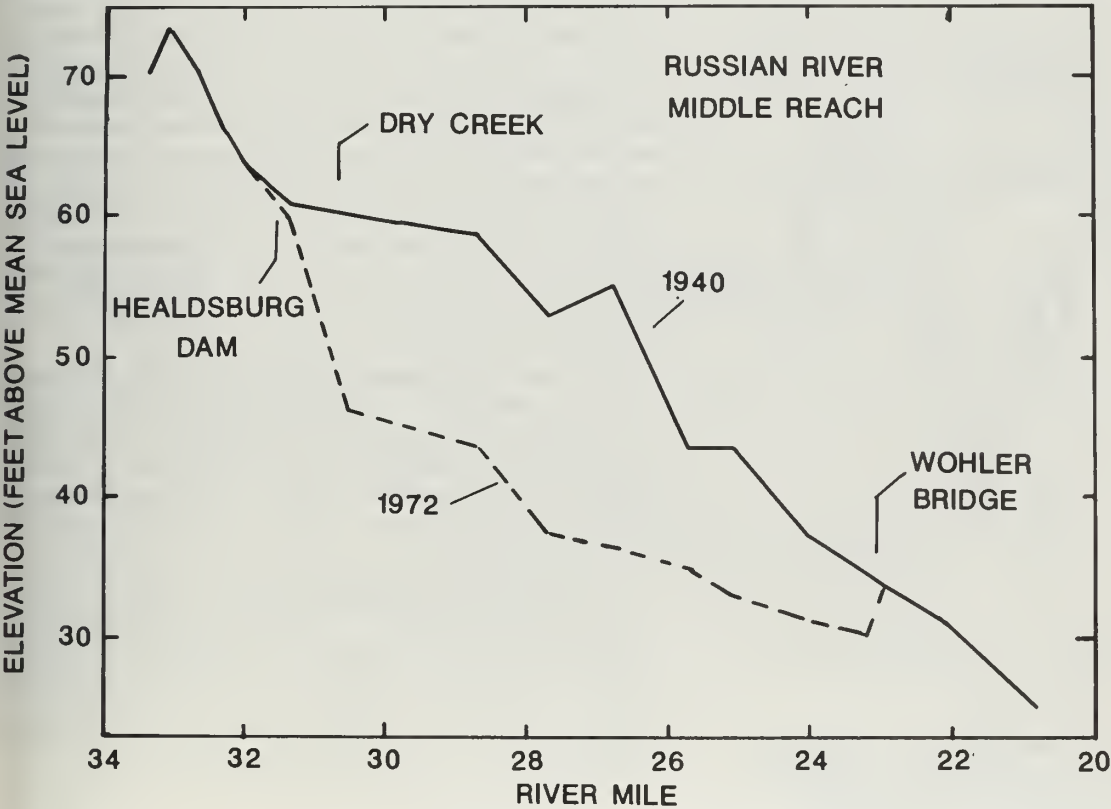


Figure 15. Change in river thalweg elevations in the Russian River middle reach between 1940 and 1972. From data provided by the U. S. Army Corps of Engineers, San Francisco District.

Exact historical extraction data are not available. Information collected by Simons and Li (1980) indicates that about 23 million tons were extracted between 1946 and 1971. This figure apparently represents total production. According to the Sonoma County Planning Department (1981), most operators moved from the riverbed to terraces by the mid-1960s, so that this figure would represent an overestimation of river gravel extraction. Because of uncertainty about the relative importance of in-channel versus terrace sources, comparing the degradation and extraction amounts is not possible. However, it is clear that extraction and degradation are spatially linked. At the upper end of the reach, Healdsburg Dam (Figure 14) could not have withheld an amount of bedload significant enough to effect the downstream degradation because flash boards are removed during the winter when bedload is transported. Moreover, even if all of the bedload for the 1940-1972 period had been trapped behind the dam, the amount would have been several hundred thousand tons, a small amount compared to the total downstream degradation.

In Dry Creek at a gage at RM 12 (Figure 14), the U.S. Geological Survey measured bedload for eight years (1979-1986); the flux averaged 22,000 t/yr, or 16 percent of measured suspended load during the eight-year period. (This higher proportional relation between bedload and suspended load is consistent with the steepness of Dry Creek and the proximity of headwater sources, and compares with a 13 percent relation measured in Redwood Creek, another steep coastal California stream described in a succeeding case study.) The two-year average for 1985 and 1986 is 9,200 t/yr. This amount is the best estimate of current average transport since closure of Warm Springs Dam in 1984 reduced the drainage area of Dry Creek by 60

percent. Because of deposition and attrition of bedload in Dry Creek downstream of the measurement site at RM 12, the bedload contributed to the Russian River would be less than the amount measured at RM 12.

Profiles of the Dry Creek channel are available for several dates since 1964. Figure 16 shows changes in bed elevation between 1964 and 1984 and indicates local degradation. Each localized site of degradation is associated with a site of gravel extraction (Sonoma County Planning Department, 1981). One datum is available for the period prior to 1964 at RM 2.1 where the bed was 6 feet above the 1964 elevation. The changes in bed elevation in Dry Creek have been interpreted as primarily a response to bed elevation changes in the Russian River (Simons and Li, 1980). However, the U.S. Army Corps of Engineers survey data show that the lowering in the Russian River at the Dry Creek mouth (10 feet according to Figure 15) was less than that recorded upstream in Dry Creek (13 feet at RM 2.1) during the same period. Moreover, the degradation in Dry Creek is clearly shown in Figure 16 to be local.

As in the middle reach of the Russian River, while extraction records are not complete enough to allow reconstruction of an exact mass balance, degradation has resulted from extraction which far exceeds replenishment. About 2.1 million tons of sand and gravel were removed between 1964 and 1984 in the vicinity of the operations near RM 2.1 alone (Simons and Li, 1980; Sonoma County Planning Department, unpublished data), thus furnishing a minimum extraction amount for Dry Creek. Extrapolating the 22,000 t/yr rate, replenishment during the same period would have been about 0.4 million tons. The cross-sections indicate that during this same period about 2.2 million tons were removed from Dry Creek by bed degradation.

As a result of a review of the data available in 1981, the Sonoma County Planning Department in their Aggregate Resources Management Plan (1981, p. 185) concluded that the "lack of knowledge about the hydrologic consequences of instream mining necessitates a comprehensive monitoring system of the hydrologic characteristics of the river channel." Cross-sections of individual gravel bars have been made semi-annually since 1981 to monitor gravel accretion and extraction. The results of this effort are not yet available. Production records have also been maintained since 1981. Annual total production from the three reaches in the lower Russian River basin in 1980-1985 averaged about one million tons per year (Sonoma County Planning Department, unpublished data).

In the upper Russian River basin near Ukiah, the California Department of Water Resources (1984) reviewed existing data, which they found to indicate that degradation has occurred at various bridge sites near zones of gravel extraction. Gravel deposits are presumably thinner in this upper basin than in the lower basin, resulting more readily in the exposure of resistant substrates. The report indicates that in some locations where gravel has been depleted from channel beds, clay layers have been exposed. Residents have reported in some locations that water levels in wells have dropped and that riparian vegetation has died, which could also be a consequence of dropping water levels. Gravel extraction effects and replenishment are of local concern, but a systematic analysis has not yet been undertaken (B. Millar, Mendocino County Planning Department, written communication).

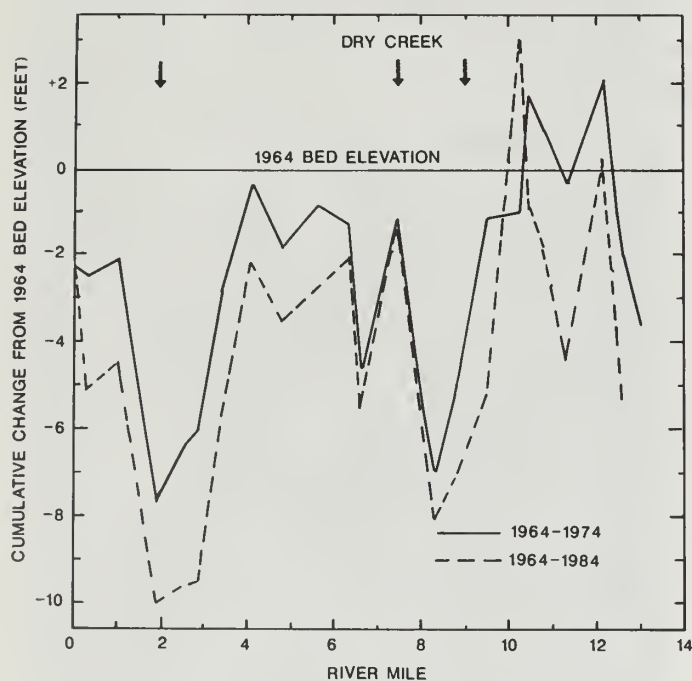


Figure 16. Cumulative change from 1964 bed elevation, 1974 and 1984, in Dry Creek, from the mouth to RM 14. Arrows indicate location of gravel extraction operations, from Sonoma County Planning Department (1981). Data from Corps of Engineers profiles, tabulated in Harvey and Schumm (1985). Each point represents average of three cross-sections at each location.

Tujunga Wash, California

Many channels in arid and semiarid settings receive water from their drainage basins only rarely, in the form of rapidly generated floodwaters. Gravel mining in these channels between flood events can cause catastrophic upstream and downstream erosion to occur in a subsequent flood. This case history of such an event in southern California is summarized from Scott (1973) and Bull and Scott (1974).

Dramatic effects of gravel mining became apparent in 1969 in the inactive channel of Tujunga Wash, the major drainage from the western San Gabriel Mountains to the extensively urbanized San Fernando Valley of southern California (Figure 17). Tujunga Wash flows on the upper part of an alluvial fan, which is confined between the San Gabriel Mountains and the Verdugo Hills. In the inactive south channel of the wash, two miles below the mountain front, a gravel pit approximately 1,000 by 1,500 feet and 50 to 75 feet deep had been the site of sporadic mining operations since 1925. Most historical discharge from the 115-square mile drainage area had, prior to 1969, been confined to the active northern channel. Both channels diverge from the head of the fan.

Closely spaced storms occurred in early 1969, both of which yielded discharges that on average would be expected no more than

once every 50 years. Peak discharge in Tujunga Wash below a flood-control reservoir was about 17,000 cfs. The previously inactive southern channel captured a major part of the storm discharge, resulting in effects that were greatly aggravated by the gravel pit. Two miles downstream, the south channel flow broke through small levees designed to divert only local runoff; this flow entered the gravel pit, triggering headward scour. Flow in the north channel also broke through unstabilized levees and entered the pit, which extended from the south bank of the south channel nearly to the center of Tujunga Wash. The centers of both the north and south channels underwent net vertical scour extending as far as 2,600 to 3,000 feet upstream of the pit to depths greater than 14 feet, and resulted in the failure of three major highway bridges a short distance upstream of the pit.

The pit acted as a trap for the sediment load of the stream, causing the under-loaded flow to scour the channel bed downstream. Flow from both channels combined within the pit and then left it along the course of the south channel, abandoning the previously active north channel and destroying a long section of four-lane highway.

This event emphasizes the need for an assessment of the geomorphic setting when issuing gravel-mining permits in seemingly inactive channels, as well as the need for a survey of existing operations in similar geomorphic settings.

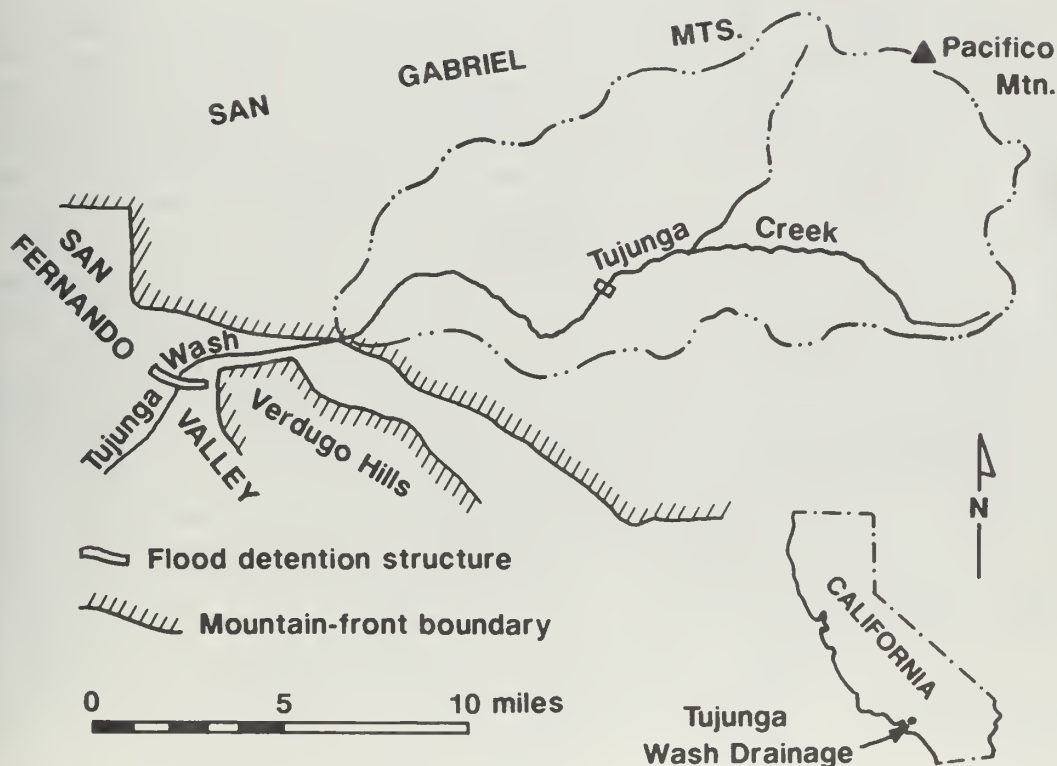


Figure 17. Location of Tujunga Wash.

White River, Washington

Gravel has been extracted from the lower White River for a number of years, partly for the purpose of maintaining flood conveyance capacity, which has been presumed to have decreased as a result of in-channel sedimentation. However, until recently no systematic monitoring of offtake, bed-elevation change, and transport rate had been made to guide the removal. Such a study is presently underway, making use of transport measurements and cross-sections taken in the past decade (Prych, 1988). This case study illustrates how channel incision of a geologically young terrane can provide a significant source of sediment and how the geologic history of a river basin can create an environment which favors rapid aggradation and degradation. The use of stream gaging and of bed profile data to characterize bed elevation changes is also illustrated.

The lower White River is supplied with a load of mostly sand and silt from its headwaters, which include several glaciers on Mount Rainier (Figure 18). Our field observations indicate that most of the coarse load of the lower river is supplied from farther downstream by trenching of a glacial moraine at the Cascade Range mountain front and of the deposit of the Osceola Mudflow, a huge mudflow originating on Mount Rainier about 5,000 years ago (Mullineaux, 1970). This mass of bouldery, sandy clay flowed down the White River valley and northwestward into the Puget Sound lowland, eventually covering 65 square miles, including the modern sites of Buckley, Enumclaw, and Auburn (Figure 18). The mudflow diverted the White River from its former southward course to a new course northwestward across the mudflow deposit to the Duwamish Valley at Auburn. Since that time the river has trenched the mudflow deposit and the underlying glacial deposits. The resulting canyon extends from near Buckley, where it

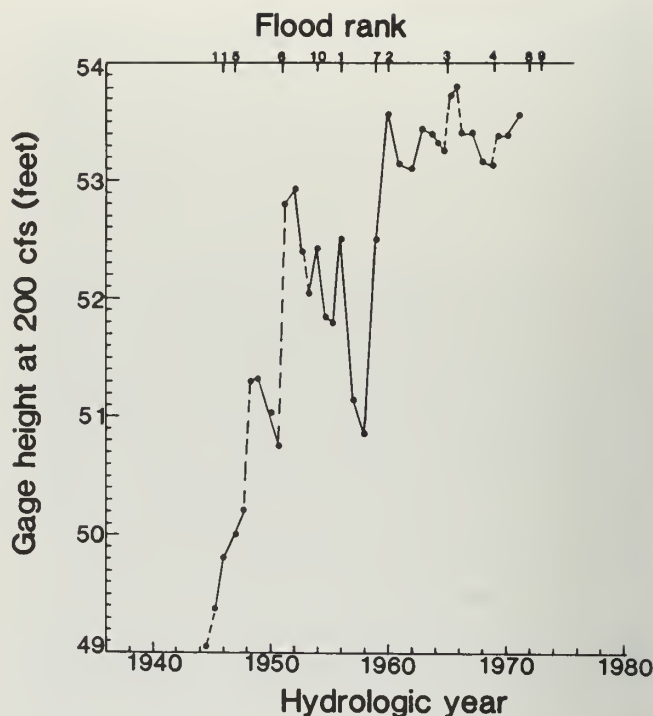


Figure 19. Gage height at a flow of 200 cfs on the White River near Sumner, 1945-1971.

is 70-100 feet deep and 2,000 feet wide, to Auburn, where it is 160 feet deep and 2,500 feet wide. The White River is probably continuing to incise the canyon and to remove sediment from it between RMs 25 and 7.

As it has trenched the Osceola Mudflow, downstream the White River has deposited sediments in a long, narrow fan which initially grew into the Duwamish arm of Puget Sound, eventually extending into the Puyallup River basin near Tacoma and the Duwamish River valley near Seattle. Until the early part of this century the White River flowed both north and south from the head of this fan at Auburn, joining both the Green River to the north and the Stuck-Puyallup River system to the south (Figure 18).

By 1892 landowners in the Green River valley were deliberately encouraging the White River floodwaters to flow down the Stuck River to relieve the flood hazard. A landslide in 1898 and a flood, aggravated by a log jam, in 1906 completed the process of diversion, and the entire White River flow cut a new channel and poured into the Puyallup River. The diversion was made permanent by diking and dredging in 1907. Since that time the channel has been locally straightened and subject to gravel extraction. Effects of these historical activities on the river morphology have not been formally studied.

Although only partial records are available for the period between 1975 and 1985, gravel extraction rates are known to be high. No records are available before 1975. Between 1975 and 1985, Pierce County and the Inter County River Improvement Agency oversaw the removal of 70,000 yd³/yr in the mile downstream of the R Street Bridge (RM 6.5-RM 7.5) and the half-mile downstream of the 8th Street Bridge (RM 4.9-RM 4.4). Private operations during this time are thought to have removed an additional, unknown amount that may be as large as the amount removed by the public agencies.

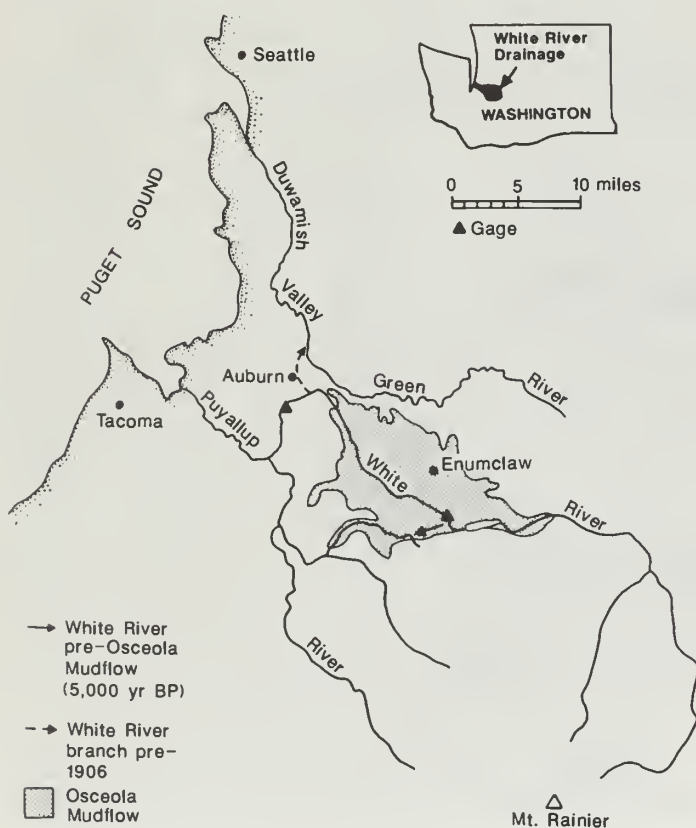


Figure 18. Location of the White River area.

An indication of recent bed-elevation trends is given by the record of bed elevation at the "Near Sumner" gage (RM 4.9) maintained by the U.S. Geological Survey. Figure 19 shows a 4.5-foot rise between 1945 and 1961, after which time the bed remained stable until the gage was discontinued in 1971. The gage site is located downstream of the canyon on the fan reach and would be expected to aggrade because of the sharp reduction in the river gradient at the junction of the canyon reach and the lowland. The record of accumulation is extended in time and space in Figure 20 which shows degradation and aggradation as measured from channel capacity surveys made in 1974/1977 and 1984 between the mouth and RM 11. The record shows a general trend of aggradation in the lower reach downstream of extraction operations and of degradation upstream. The survey results indicate that in a 10-year period, 43,000 cubic yards of bed material accumulated in the channel downstream of RM 11.

These data are difficult to evaluate without more completely documented extraction amounts. The abrupt apparent stabilization of bed elevation at RM 4.9 may be related to increased extraction, which may have begun at that time, or it may be unrelated. Similarly, whether the degradation upstream of RM 9, in the lower part of the White River canyon, reflects long-term geologic trends or the effects of gravel extraction that may have taken place in this reach is not known. However, if extraction has been confined to the two identified locations, present data are consistent with an interpretation of long-term aggradation in the lower fan reach, and degradation in the upper canyon reach, with local degradation related to gravel removal operations.

A minimum rate of bedload transport into the lower White River may be derived from the combined cross-sectional and extraction data. If an average of 43,000 yd³/yr of material is accumulating in spite

of a minimum of 78,000 yd³/yr of removal during the 10-year period, then the minimum transport must be 121,000 yd³/yr. This is a minimum influx because some of the bed material is transported out of the reach into the Puyallup River and because gravel extraction records are incomplete. As more complete extraction records and sediment transport measurements become available, it may be possible to determine the locations and rates at which the channel aggrades and degrades in the absence of gravel extraction, and to define a transport rate more precisely.

Redwood Creek, California

Redwood Creek drains a 720 square kilometer (278 square mile), northwest-trending, elongate basin in north-coastal California (Figure 21). The basin has undergone rapid tectonic uplift within the last two million years and is underlain by highly sheared and mechani-

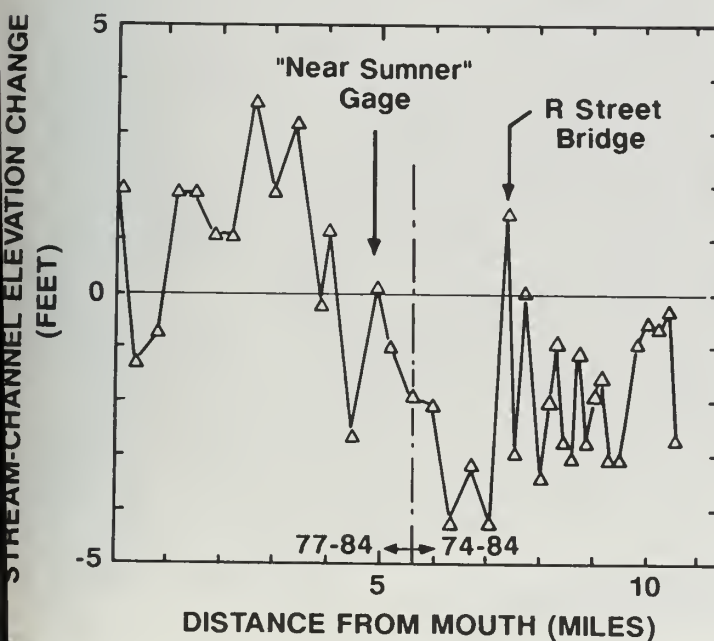


Figure 20. Changes in elevation of surveyed stream channel cross-sections.

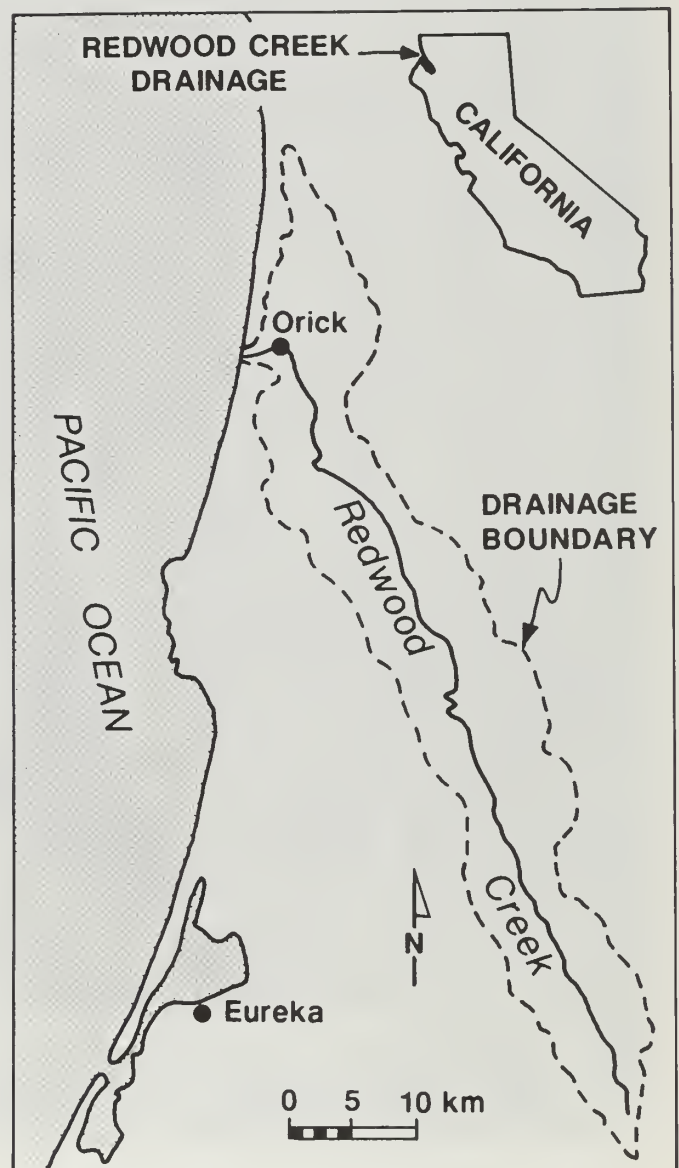


Figure 21. Location of the Redwood Creek drainage basin.



Photo 4. View of Redwood Creek as it enters the Pacific Ocean near Orick, California. Redwood Creek was mined in summer 1987 and in summer 1988, when this photo was taken.

cally weak sandstones, mudstones, and schists of the Franciscan Assemblage. The combination of rapid uplift, unstable materials, and seasonally high rainfall has resulted in high sediment yields. In addition, Madej (1984) indicates that sediment yields measured since extensive timber harvest began are several times yields estimated for the undisturbed condition. Timber harvest began in the mid-1950s, with 45 percent of old-growth having been logged by 1962, and 81 percent by 1978.

Redwood National Park was established in 1968, and included a 0.5-mile wide corridor along Redwood Creek in the lower one-third of the basin. Following establishment of the park, controversy arose over the damaging



Photo 5. Redwood Creek looking upstream toward Highway 101 bridge from near point A in Figure 22. Photograph taken in October, 1987 following mining. Note flat channel bed, shallow linear trough transmitting water in channel center.

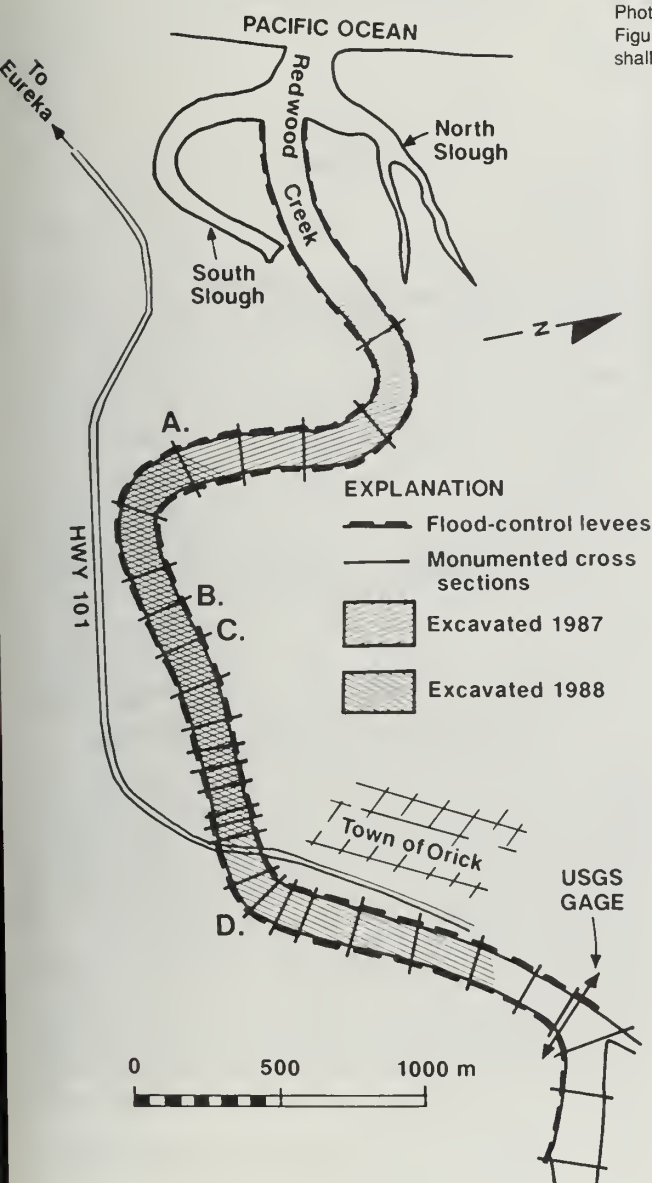


Figure 22. Map of the mined reach of Redwood Creek near Orick. Twenty-nine cross sections document channel changes in the 5-km reach, and the U.S. Geological Survey gaging station at the upstream end of the reach provides water and sediment discharge data. Cross-sections A-D refer to Figure 23.

effects of logging upstream and adjacent to Redwood Park, especially in conjunction with a large flood in December 1964. The U.S. Geological Survey documented significant aggradation in Redwood Creek and the impacts of clearcut logging on forest ecology and the aesthetic values of the Park. A decade of political discussion and scientific research culminated in the expansion of Redwood National Park in 1978 to include the lower 197 square kilometers of the basin, from the watershed divides to the creek. The balance of the watershed remains in timber production. Downstream of Redwood Park, the channel of Redwood Creek was channelized between levees constructed in 1968 by the U.S. Army Corps of Engineers (Photo 4).

At Rkm 5, at the upper end of the channelized reach and 1 km upstream of the town of Orick and Highway 101, the U.S. Geological Survey since 1953 has measured the discharge of water and suspended sediment, and since 1971, bedload. Long-term estimates of suspended sediment discharge for the period 1954-1980 were estimated to be 1,480,000 tons/yr (U.S. Geological Survey, written communication to Redwood National Park, 1981). Estimated bedload discharge for the same period was 191,000 tons/yr, or 11 percent of the total load (13 percent of suspended load). Ratings for bedload were shown earlier in this publication as Figure 4.

In summer 1987, Humboldt County began a program of annual gravel mining from between flood levees (Figure 22). Because of concern over potential effects of the mining on riverbed morphology, which could in turn affect the quality of habitat provided for fish migrating upstream to spawning grounds within the Park, Redwood National Park personnel initiated a monitoring program prior to gravel removal in summer 1987. An additional concern was the potential for undermining of the flood levees due to bed degradation. A series of cross-sections was installed (Figure 22), to be periodically resurveyed, with the goal of determining offtake and replenishment during the intervening high-water seasons and to document changes in channel morphology. Gravel was to be excavated by scrapers to the low-water level, and a low-flow trough was to be maintained (Photo 5). There was concern that the stream would have a limited efficacy at reestablishing its pool-riffle structure, because the tidal influence on the reach would limit the scour depth, and morphologic recovery would depend on the rebuilding of bars from replenished material. Offtake was to be limited to the average annual bedload transport estimated from the 1954-1980 data.

Comparison of cross-sections surveyed in the spring and fall of 1987 indicated that 102,000 cubic meters were excavated during summer of 1987. Resurvey of cross sections in April 1988 indicated that the winter floods redeposited 49,000 cubic meters. Bedload measurements by the U.S. Geological Survey during the 1987-1988 high-flow season indicated a transport of 29,000 cubic meters. Field observations by Redwood National Park personnel suggested that the surveyed replenishment may have been greater than the measured upstream transport because some of the replenished volume could have eroded from the unmined channel downstream of the gage. It is also possible that the coarsest portion of the suspended load deposited in the mined reach. Finally, channel changes caused by mining may have added to the existing sources of imprecision associated with estimating annual bedload transport from bedload sampling. Cross-sectional changes between the summer and fall of 1988 indicated offtake of 87,000 cubic meters. More current replenishment and transport data are not available at the time of writing in spring 1989.

Figure 23 shows how the channel cross-section has changed at four representative sites in the mined reach. The channel changes are described in detail in the figure caption. Taken together, the cross-sectional changes illustrate several findings. First, bars were able to rebuild only a fraction of the topography removed by mining during the course of a high-flow season (although this was complicated by the 1987-1988 rainy season having transported lower than average bedload). The channel bed was destabilized with some bars rebuilt along the opposite bank from their original location. Channel bed degradation proceeded upstream of the mined reach. Finally, low-flow channel depths were not restored by scour during high flows.

As a result of the implications for aquatic habitat of the morphologic changes indicated from these preliminary results, the California Department of Fish and Game, an agency responsible for permitting the mining, has proposed revisions to the permit. Rather than allowing mining down to the low-water level, mining will be restricted to one-half the channel width and will be focused in the low-water channel. The low-water channel will be temporarily dewatered to minimize sedimentation during extraction. The sinuous channel plan form and bed morphology existing prior to mining will be conserved during mining. The monitoring program being carried out by Redwood National Park will be continued to document and evaluate the results from this modified approach. Limits to annual offtake may also be reviewed as more years of annual transport data become available. Analysis of this data can determine whether average annual transport has changed or remained the same compared to the 1954-1980 period.

Skykomish River, Washington.

Because of increased pressure to mine gravel from the channel bars in the Snohomish River system, in 1979 the Snohomish County Planning Department commissioned a study of existing levels of gravel removal on channel changes. The case study illustrates how analysis of sequential aerial photographs can be used along with knowledge of transport rates and offtake amounts to determine rates at which gravel can be extracted without major disruptions to the adjoining bars and banks (Dunne, 1979; Dunne and others, 1981). The analysis did not consider changes to bed elevations, which may or may not have occurred.

The Snohomish River basin drains 1,780 square miles of the western Cascade Range (Figure 24). The Snohomish River is formed by the confluence of the Snoqualmie River from the south and the Skykomish River from the north. The upper parts of both rivers flow

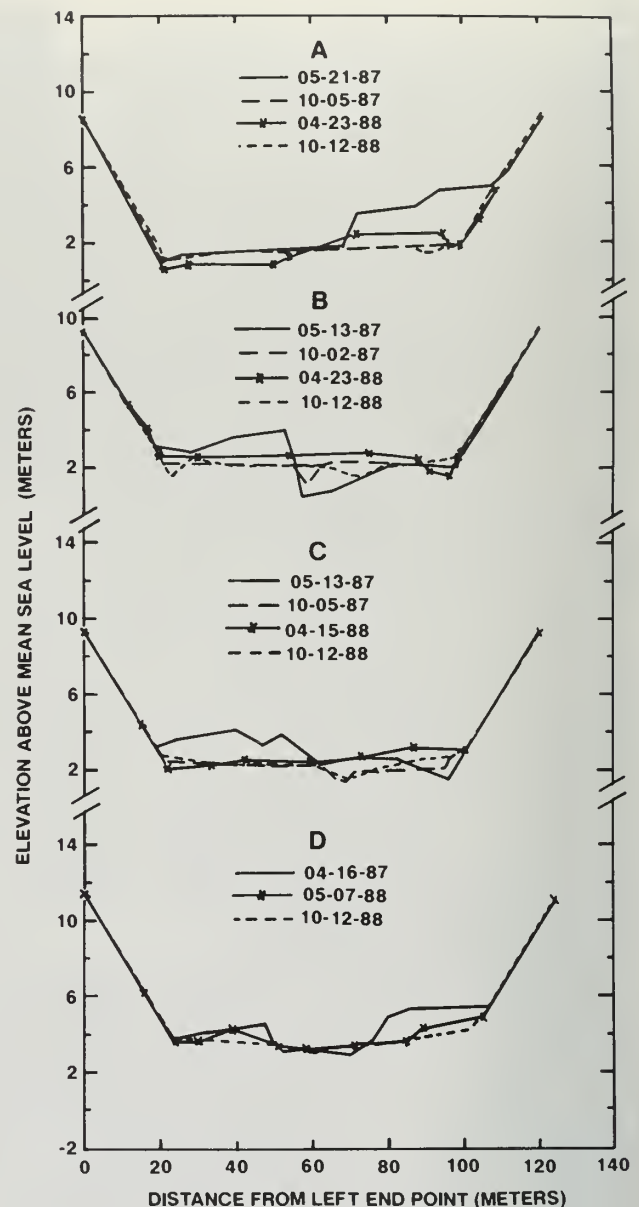


Figure 23. Record of periodic cross section resurvey in the mined reach of Redwood Creek. Data provided by D. K. Hagans, Redwood National Park.

- (A) Large right-bank point bar, shown in May 1987 survey, was removed in the subsequent summer, leaving a flat bed. Winter flows replenished less than a third of the bar (April 1988 survey), and downcut the channel thalweg almost one meter. Excavation in summer 1988 lowered the channel bed by one-half meter, and returned the channel to a flat configuration (October 1988 survey). Bar replenishment in this downstream location was less than in upstream locations.
- (B) Low-flow channel is well developed in May 1987 survey; following mining the bed appears flat with small center incision (October 1987). Winter flows did not rebuild the left-bank bar, but shifted the thalweg to the base of the right bank and filled the channel to a depth of one-half meter (April 1988). Excavation in summer 1988 lowered the channel by one-half meter, and created a flat bed (October 1988).
- (C) Well-developed left-bank bar, replaced by flat bed with a poorly defined incised channel after mining in summer 1987. Subsequent winter flows filled the channel on the opposite, right bank side. Excavation in 1988 replaced topography with flat bed.
- (D) Cross-section site was not mined in 1987, but gravel was extracted immediately downstream. Prominent right-bank gravel bar (April 1987) degraded substantially during subsequent winter flows (May 1988) in response to downstream mining. Gravel extraction in 1988 created flat bed (October 1988).



Figure 24. Location of the Skykomish River, Washington.

through valleys sculpted by alpine glaciers. The longer Snoqualmie River descends to and meanders across the Puget Sound lowland before it reaches the Snohomish River, at which point it transports little gravel. The Skykomish River maintains a steeper gradient and carries a coarse load to the Snohomish River. The lower reach of the Skykomish and the upper Snohomish were the focus of this study.

Between the towns of Index and Startup, the Skykomish River is cutting into gravelly and bouldery terraces formed by meltwater from the alpine glaciers and is carrying downstream those sediments which are small enough to be moved. Downstream of this erosional zone is a transitional zone between Startup and about a mile below Sultan, in which there is little net deposition or erosion. The third zone, below-Sultan, is depositional and the river migrates across the valley floor, leaving channel bar and overbank flood deposits. Based on bedload transport rates estimated from suspended and bedload sediment sampling for the Skykomish and the Snohomish rivers (Figure 25) near Monroe, an estimated 21,000 yd³/yr and 15,000 yd³/yr are transported in the two rivers, respectively. At least 6,000 yd³/yr, but no more than 21,000 yd³/yr, is deposited between Monroe and the confluence with the Snoqualmie River. This is known because the Snohomish River transports a portion of the finer-size fractions of the Skykomish River bedload, with most gravel being deposited just below the confluence but some moving past at least three miles beyond the confluence. Some of the bedload in the Snohomish River probably originates as suspended load in the steeper Skykomish River. Most of the sandy bedload of the Snoqualmie River at the confluence is fine enough to go into suspension once it is transported into the steeper, deeper Snohomish channel.

To determine how varying amounts of extraction affected adjacent bars and banks, aerial photographs were examined of the channel in the vicinity of three gravel bars from which extraction occurred. One example is given below. On the north bank of the Skykomish River at RM 2.7, a bar was undisturbed in the period spanned by aerial photographs taken in 1948 and 1961. During that period parallax-bar

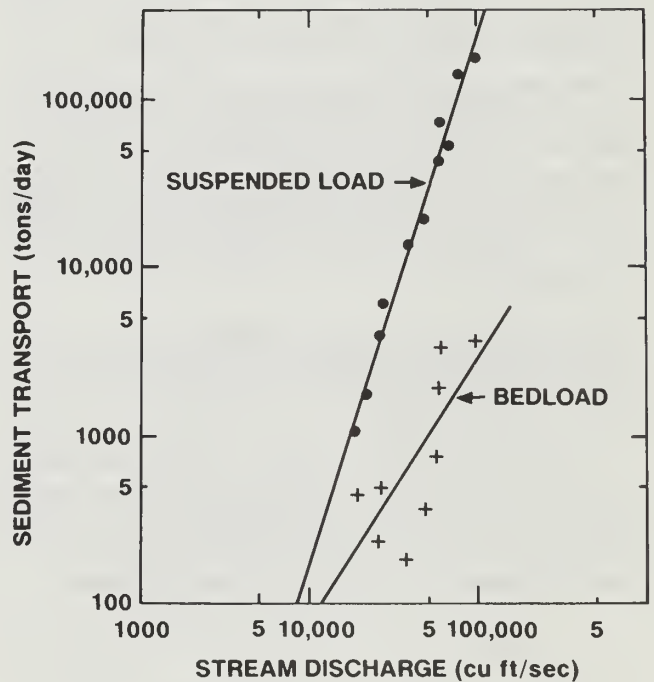


Figure 25. Bedload and suspended load rating curves for the Snohomish River near Monroe. Combination of the rating curves with 10 yr of flow data indicate an average bedload transport of 26,000 t/yr (15,000 yd³/yr) and annual suspended load transport of 500,000 t/yr. Bedload is 5 percent of suspended load.

measurements of elevation change using sequences of aerial photos showed that the bar accreted at a rate of about 5,000 t/yr (3,000 yd³/yr). Gravel extraction began in 1961 with an average removal of 84,000 t/yr (50,000 yd³/yr). The bar itself was considerably dimin-

ished in size by 1969, and neighboring bars on both the upstream and downstream sides were also diminished. Between 1969 and 1976, the offtake was reduced to 25,000 t/yr (15,000 yd³/yr), and the bar grew slightly, although the neighboring bars did not. Between 1976 and 1979 extraction averaged 17,000 to 25,000 t/yr (10,000 to 15,000 yd³/yr) without further changes to channel morphology, although the bar did not recover its former size. The analysis reveals that about 20,000 t/yr (12,000 yd³/yr) can be extracted from this bar without causing a long-term erosive trend on other bars.

No mining occurred between 1948 and 1961 on the downstream bar at RM 0.2, and an average annual incremental increase of 12,000 t/yr (7,000 yd³/yr) occurred. Between 1961 and 1969, the bar shrank in size, probably as a result of extraction from the bar upstream. This observation suggests that extraction can be competitive between

neighboring bars and that to avoid effects to neighboring bars offtake amounts must be divided among neighboring operations.

Extraction from the bar at RM 2.7 has also changed rates of bank erosion at the bend and downstream. On the outside of the bend, the erosion rate had been 10 and 20 ft/yr and averaged 15 ft/yr between 1933 and 1961. Since mining began in 1961, the bend has been stable up to 1978. Erosion has also been slowed at the outside bank near the downstream bar at RM 0.2. During the 1961-1969 period, bank retreat averaged 20 ft/yr, less than the 34 ft/yr between 1955 and 1961, and the 36 ft/yr between 1969 and 1978. This is an example of an instance where bank erosion was reduced by bar scalping.

MacDonald (1988) provides a second example of how erosion of downstream bars can result from extraction upstream, in this case from pits in the channel of the Naugatuck River, Connecticut.

DISCUSSION OF CASE STUDIES

Taken together, the case studies illustrate much of the material presented in the first three parts of this report. Differences in the location and nature of sediment sources cause differences in the gravel supply; downstream changes in gradient and thus of transport and deposition influence the location of gravel deposits.

The case studies illustrate that some geologic environments favor high rates of aggradation, whereas others favor degradation or an approximate equilibrium between sediment supply and transport to downstream reaches. The rate and direction of long-term change in bed elevations can be predicted or rationalized by an understanding of the recent geologic history of the area and confirmed by historical information, such as cross sections from bridges, stream gages, and channel surveys.

The case studies illustrate several methods for determining bedload transport and demonstrate that the rapid estimation of bedload transport rate is almost always possible even when it is necessary to rely heavily on existing data.

Several of the case studies document bed degradation resulting from extraction in excess of upstream supply. Degradation appears to extend up to several miles upstream of an operation. Bank erosion is a more local effect, specific to particular bends or reaches, and occurs in response to particular modifications to channel geometry.

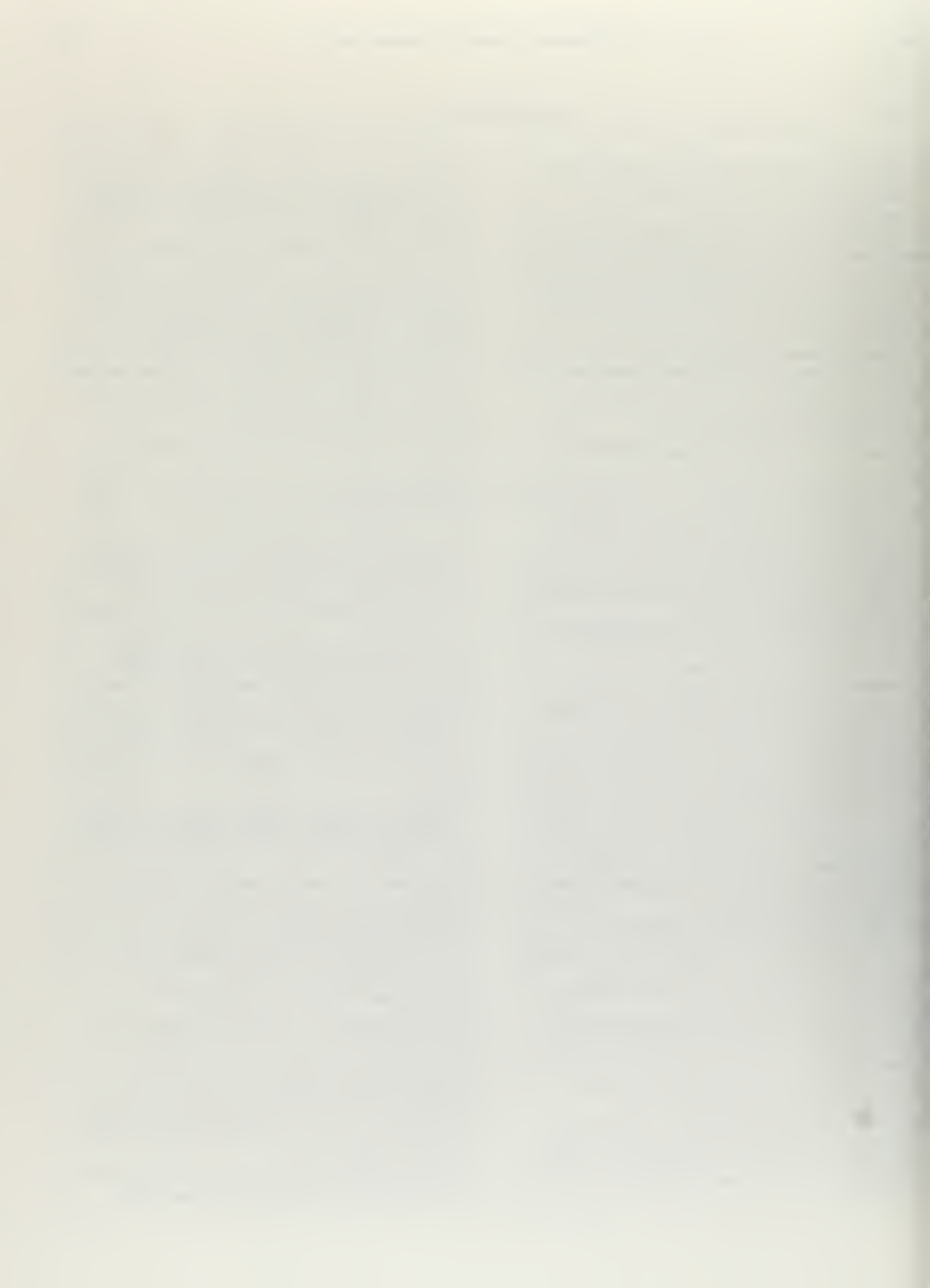
The case studies illustrate that the significance attached to different effects of gravel extraction on channel morphology varies among different communities. In some cases, the dominant concerns were the potential effects on fisheries, while in other, more intensively agricultural or urbanized areas, dominant concerns were flood control, effects on groundwater, or the potential for property loss and damage to engineering structures by bank erosion.

Detailed analysis of ecological effects of gravel extraction is beyond the scope of this report. However, the case studies illustrate how analysis and understanding of the physical effects are frequently a necessary, tractable precursor to evaluation of ecological effects. Examples in the case studies of how ecological effects can result from physical changes include the scouring of bed gravels and exposure of underlying substrates not suitable as habitat, and the destruction of pool and riffle structure which is important for habitat.

In few river basins have historic or projected future effects of gravel extraction been determined, nor have policies been developed for managing the identified effects of gravel extraction. It is hoped that the presentation of these preceding case studies of rivers in which the process of study and policy making has begun along with the general discussions of river channel geomorphology and gravel extraction will promote creative river basin planning.

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